NASA CR- 166665

SQ1

NAS5-20936

Dynatrend, Inc.

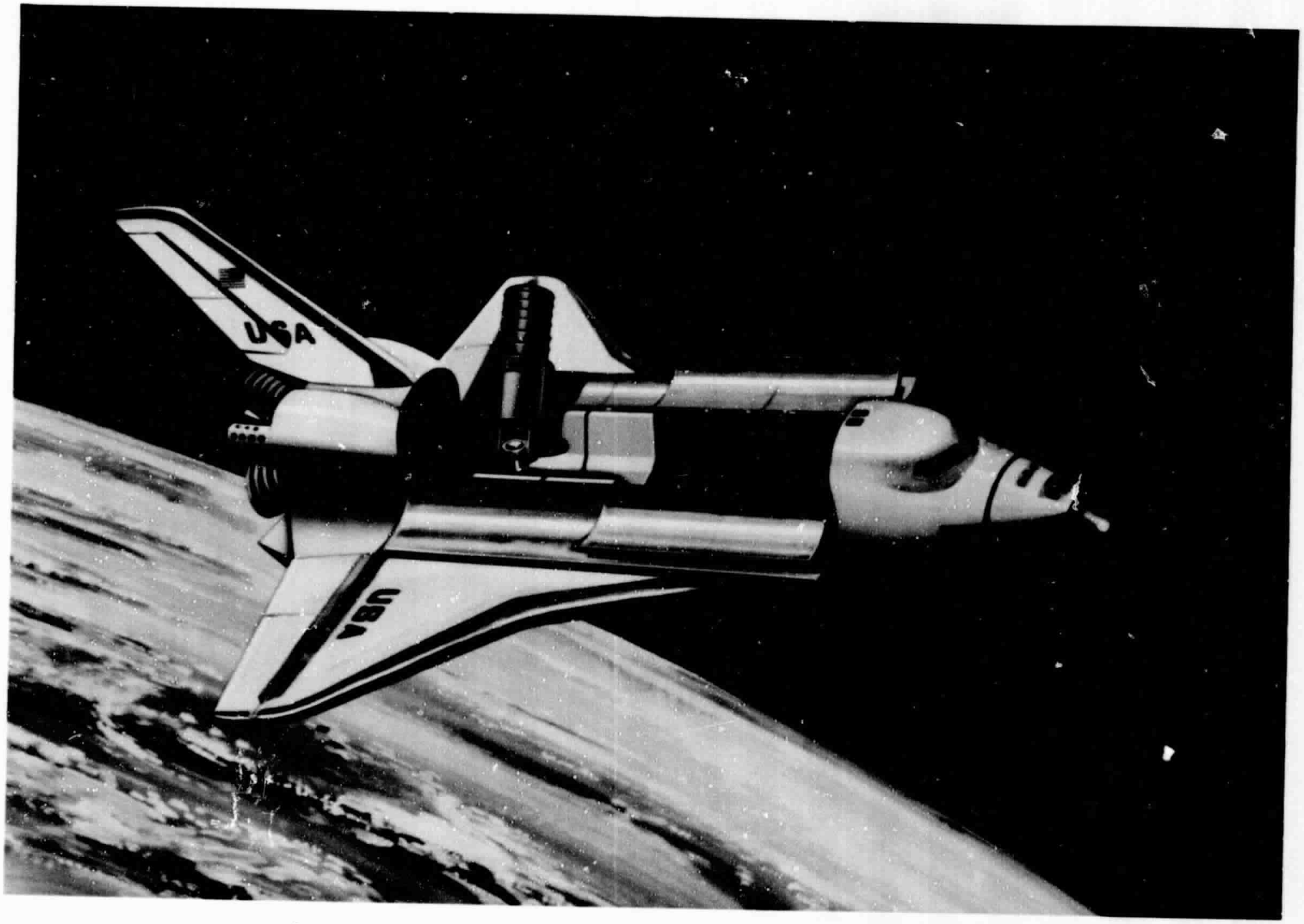
REPORT OF THE FACILITY DEFINITION TEAM SPACELAB UV-OPTICAL TELESCOPE FACILITY

(NASA-CR-166665) REPORT OF THE FACILITY DEFINITION TEAM SPACELAB UV-OPTICAL TELESCOPE FACILITY (Dynatrend, Inc., Burlington, Mass.) 109 p HC A06/MF A01 CSCL 03A G3/89
N81-26997
Unclas
28322

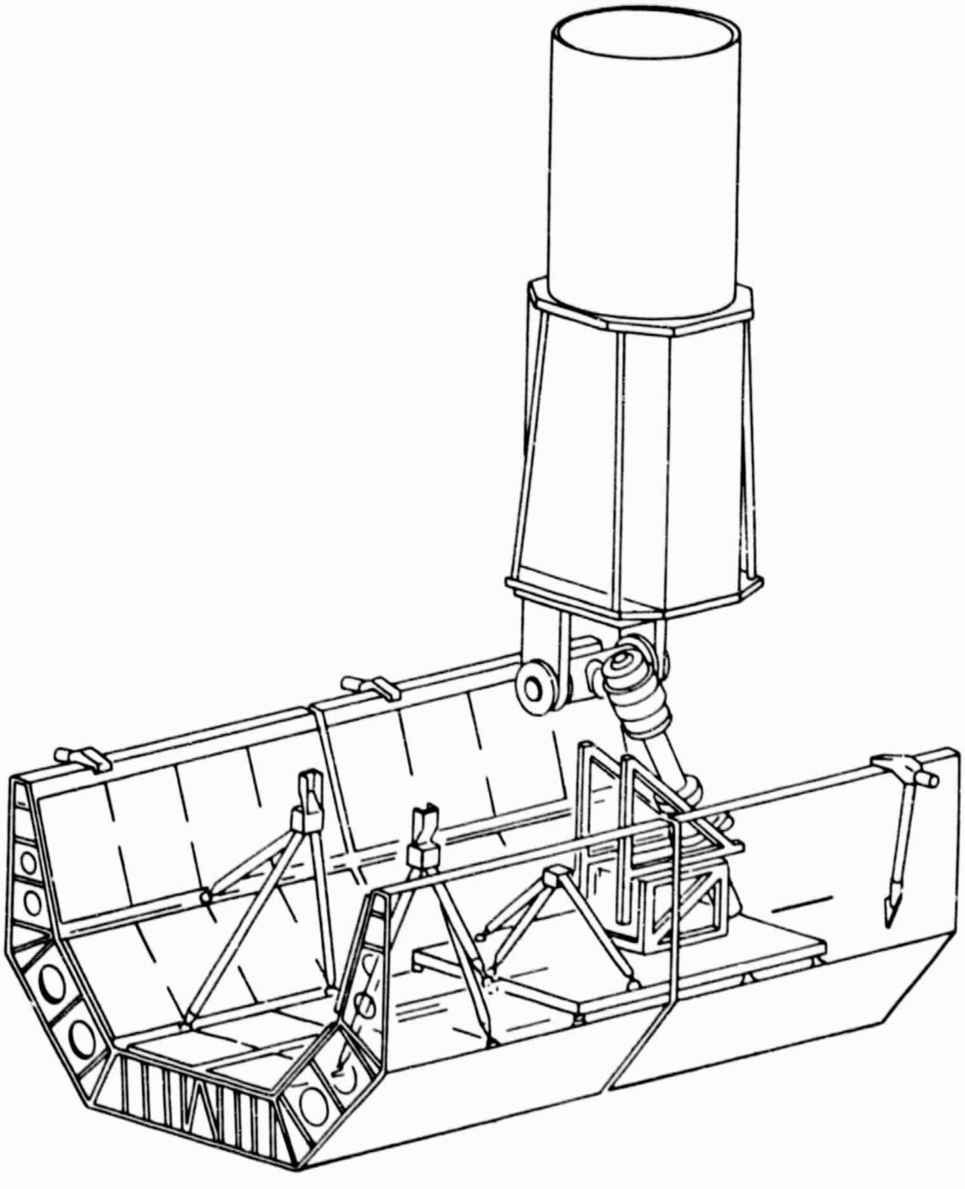
DECEMBER 1975

PREPARED BY THE
FACILITY DEFINITION TEAM

ASTRONOMY SPACELAB PAYLOADS STUDY
GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND 20771

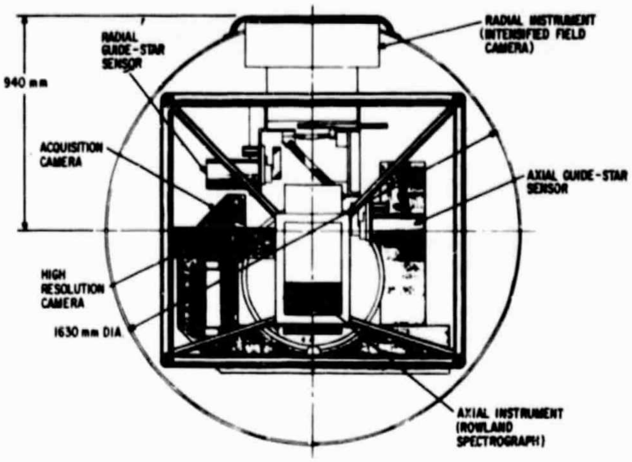


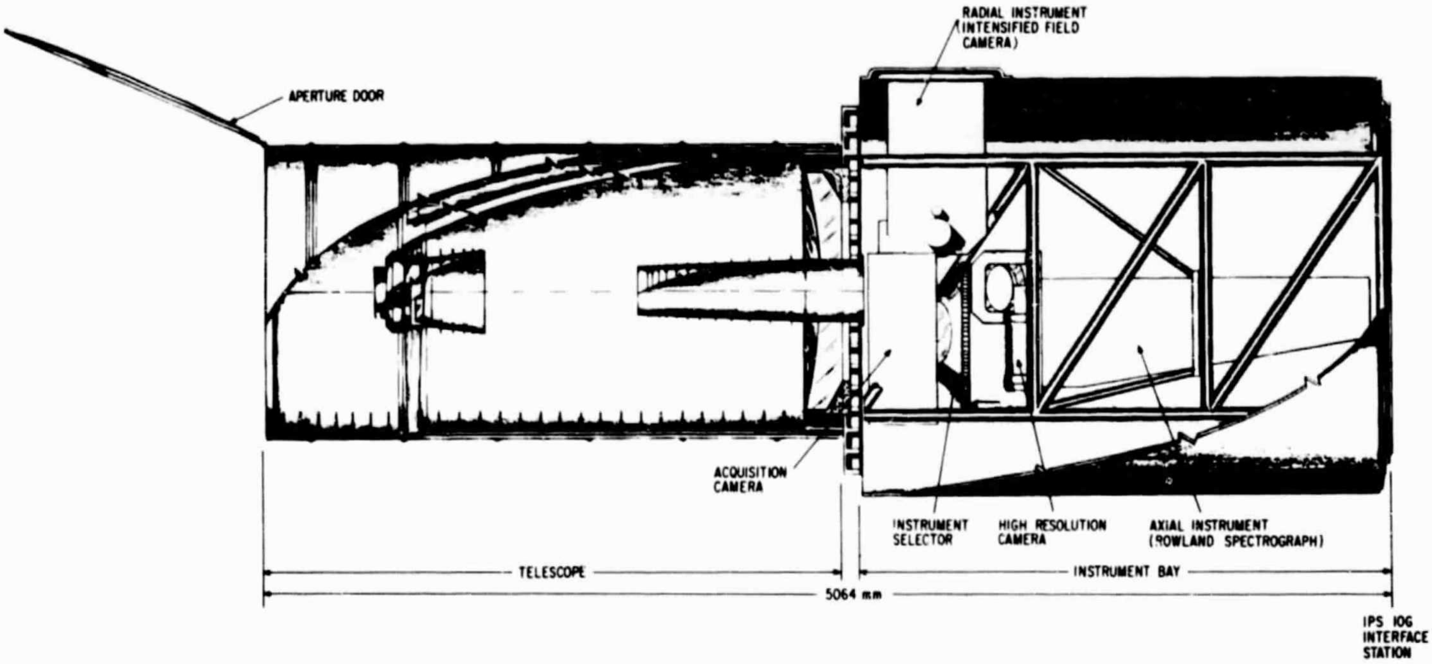
Artist's Conception of the Spacelab UV-Optical Telescope (SUOT)
in Shuttle Payload Bay

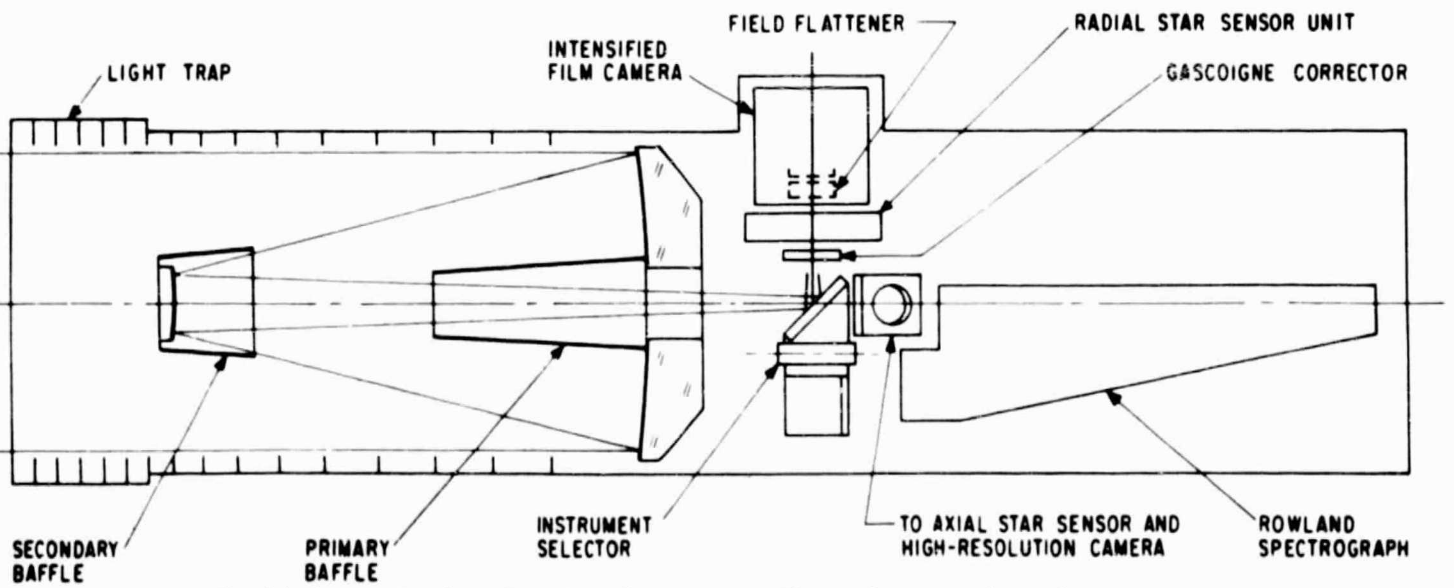


SUOT Deployed on Spacelab Pallets.

SPACELAB UV-OPTICAL TELESCOPE FACILITY







Preliminary Design Concept for SUOT. The telescope is a 1m, f/15, Ritchey-Chretien design which, with refractive correctors, will provide a flat data field 0°5 in diameter, with image diameters 0.3 arcsec at wave lengths >2000Å. The uncorrected flat field is 0°1. Interchangeable primary optics will allow periodic missions optimized for far-ultraviolet observing. The axial and radial instrument areas will accommodate a variety of instrument types. A planetary camera and a field viewing monitor may be carried on every flight.

TABLE OF CONTENTS

Page

I. Introduction.................. 1-1

II. Unique Capabilities and High Priority Programs for the Spacelab UV-Optical Telescope (SUOT)............ 2-1

III. Scientific Programs.................................... 3-1

A. High Angular Resolution Imagery Over Wide Fields... 3-1

B. Far-Ultraviolet Spectroscopy......................... 3-8

C. Precisely Calibrated Spectrophotometry.............. 3-17

D. Solar System Studies................................ 3-19

E. Other Programs...................................... 3-28

IV. Facility Concept and Specifications..................... 4-1

A. Basic Concepts and Specifications................... 4-1

B. Pallet-Mounted versus Accessible Focal Plane Configuration................................ 4-1

C. Optical Parameters.................................. 4-2

D. Instrument Mounting System.......................... 4-3

E. Pointing and Stabilization System................... 4-6

V. Illustrative Focal Plane Instruments.................... 5-1

A. Direct Imaging Camera (DIC)......................... 5-1

B. Far-Ultraviolet Spectrograph (FUS).................. 5-4

C. Precisely Calibrated Spectrophotometer (PCS)........ 5-6

D. Planetary Camera.................................... 5-9

VI. Operational Concepts.................................... 6-1

A. Makeup and Functions of Shuttle Payload Crew........ 6-1

B. Extra-Vehicular Activity (EVA) Requirements......... 6-4

C. Telescope Control and Data Management............... 6-4

Table of Contents
(continued)

Page

VI. Operational Concepts

D. Payload Operations Control Room (POCR).............. 6-8

E. Orbital Constraints.................................. 6-9

F. SUOT - Orbiter Interfaces........................... 6-10

Appendices

A. Guidelines for the SUOT Study........................... A-1

B. Limiting Magnitudes for SUOT Field Imagery.............. B-1

C. Capability of the Far-UV Spectrograph................... C-1

D. Capability of the Precisely Calibrated Spectrophotometer - Polarimeter........................ D-1

E. Typical Operational Event Sequence...................... E-1

LIST OF FIGURES

No.		Page
	Artist's conception of the Spacelab UV-Optical Telescope (SUOT) in Shuttle payload bay........	Frontispiece No. 1
	SUOT deployed on Spacelab pallets..............	Frontispiece No. 2
	Preliminary design concept for SUOT............	Frontispiece No. 3
1.	SUOT and Space Telescope (ST) fields of view projected on the Large Magellanic Cloud	3-4
2.	Copernicus spectrum scan of the 05f star ζ Puppis between 1016 and 1048Å..............................	3-10
3.	Pioneer 11 high resolution image of Jupiter............	3-24
4.	Schematic layout of far-UV Rowland spectrograph........	5-5
5.	Schematic layout of the precisely calibrated spectrophotometer......................................	5-7
6.	Preliminary concept of the payload specialist station required by the SUOT facility..................	6-6
7.	Basic orbiter roll and IPS slew requirements for viewing two or three objects per orbit.............	6-12
8.	SUOT payload chargeable weights versus mission duration (six-man crew)...............................	6-18
C-1.	Far-ultraviolet spectrograph, estimated signal quality versus wavelength.............................	C-5
C-2.	Far-ultraviolet spectrograph, cumulative available number of hot stars versus signal quality.............	C-7
D-1.	Precisely calibrated spectrophotometer-polarimeter, expected fluxes from various sources versus wavelength.	D-2
D-2.	Precisely calibrated spectrophotometer-polarimeter, cumulative object count versus expected flux at 1550Å..	D-5

LIST OF TABLES

No.		Page
1.	Observing Programs for Far-Ultraviolet (UV) Spectrograph	3-14
2.	Extragalactic Spectrophotometric Targets Observable in a Two Week Flight	3-20
3.	Spectral Lines of Special Interest in Supernovae Remnants	3-30
4.	Summary of Mechanical and Optical Specifications for SUOT	4-4
5.	Instrument Pointing System (IPS) Requirements Requested by the NASA Payload Planning Steering Group	4-7
6.	SUOT Requirements on the IPS	4-9
B-1.	SUOT Limiting Magnitudes for Point Sources	B-3
B-2.	SUOT Limiting Magnitudes for Extended Objects	B-5
C-1.	Parameters Used for Signal Quality Calculations for Far-UV Spectrograph	C-4
C-2.	Image Aberrations in Far-UV Spectrograph	C-10
E-1.	Illustrative SUOT Operational Event Sequence	E-2

I. INTRODUCTION

NASA, through the Astronomy Spacelab Payloads Study at Goddard Space Flight Center, is conducting a study of the feasibility, preliminary design and scientific potential of a general purpose, one-meter class telescope facility to be used for astronomical (non-solar) observations in the UV-optical wavelength range. This telescope will be operated on the NASA Space Shuttle with the support of Spacelab systems. The present Facility Definition Team (FDT), selected by NASA Headquarters through AO#3, is responsible for the definition of scientific requirements for this Spacelab UV-Optical Telescope (SUOT) facility and for the scientific review of related engineering design studies. The membership of this team is:

TEAM MEMBERS

C. M. Anderson, University of Wisconsin

K. G. Henize, NASA, Johnson Space Center, Team Leader

E. B. Jenkins, Princeton University

R. W. O'Connell, University of Virginia

A. M. Smith, NASA, Goddard Space Flight Center

B. A. Smith, University of Arizona

SPECIAL ADVISORS

H. Arp, Hale Observatories

W. G. Fastie, The John Hopkins University

A. B. Underhill, NASA, Goddard Space Flight Center

EX-OFFICIO TEAM MEMBERS

D. S. Leckrone, NASA Goddard Space Flight Center, Study Scientist

J. D. Rosendhal, NASA Headquarters, Program Scientist

TECHNICAL SUPPORT TO THE TEAM

M. Bottema, Ball Brothers Research Corporation

E. S. Chin, NASA, Goddard Space Flight Center

R. W. Melcher, NASA, Goddard Space Flight Center

H. B. Winkler, Dynatrend Incorporated

The major objective of the FDT and supporting engineering studies is to develop a detailed concept for the SUOT facility which is scientifically meritorious, technically feasible and relatively low in cost. The guidelines developed by NASA to define the scope of these studies are listed in Appendix A.

This report constitutes the final report of the first year's activity of the FDT. It follows the general organization of the Interim Report produced by the FDT in April 1975, and is identical in most respects except for minor modifications in some sections and major additions in one or two other sections. The most noteworthy additions are in Section VI where considerable detail has been added to the discussion of in-orbit crew functions, to the analysis of control and data management requirements, to the analysis of spacecraft maneuvering constraints, and to the study of weight considerations for 30-day missions.

II. UNIQUE CAPABILITIES AND HIGH PRIORITY PROGRAMS FOR THE SPACELAB UV-OPTICAL TELESCOPE (SUOT)

The Spacelab UV-Optical Telescope (SUOT) is envisioned to be a very flexible, general purpose facility capable of accommodating a wide variety of focal plane instrumentation in the 1981-1990 timeframe. We do not presume to be able to predict the full range of applications it will engender. For the purposes of this study, however, it is necessary to identify potential observing programs for SUOT which will serve to illustrate the scientific merit of the facility, to delineate the complementary role of this telescope relative to other space telescopes, and to provide a basis for decisions concerning telescope design. The SUOT facility will be defined so as to readily accommodate these easily foreseen programs, but careful consideration will also be given to avoiding constraints which may preclude its use for other purposes as well. We have assumed that SUOT will operate in the same timeframe as the Space Telescope (ST), and primary consideration has been given to scientific programs which complement the expected capabilities of the ST. However, we firmly believe that the SUOT has strong scientific merit in its own right, and should be optimized for those capabilities rather than for use as a test bed for ST instrumentation. If the ST should slip markedly in schedule, SUOT could provide powerful interim capability, carrying out exploratory programs in high resolution field imagery, spectroscopy and photometry in preparation for more detailed ST observations. The SUOT will, of course, not be able to compete with a "full-up" ST in terms of ultimate angular resolution or light gathering power.

The SUOT will be capable of contributing to the solution of many fundamental scientific problems at the frontiers of knowledge. The following brief but representative list of such problems illustrates this scientific potential:

1. determination of the optical structure of the massive, collapsed X-ray sources (massive black holes?) at the nuclei of highly condensed globular clusters and evaluation of the condensation parameters of those clusters through high angular resolution star counts to faint magnitude limits;
2. accurate determination of the main-sequence turn-off, and hence the ages, of a variety of star groups within the Large Magellanic Cloud to establish the overall pattern of star formation within this nearby galaxy;
3. measurement of the primordial deuterium-to-hydrogen ratio in the interstellar gas high in the galactic halo, within matter removed from the processes of nucleosynthesis which modify the composition of the

disc of our galaxy (the D/H ratio can be directly related to the present average density of the universe and hence to the closure of the expansion of the universe);

4. measurement of the total energy output and effective temperatures of stars in galactic and globular clusters, stars at the same distance which cover a wide range of mass and luminosity, as a fundamental test of stellar evolution theory;
5. determination if the water-ice clouds, associated with large volcanoes on Mars, are caused by orographic uplift or by local source degassing, possibly associated with volcanic activity;
6. measurement with high spectral resolution of the strength of the ultraviolet lines of Hg III in Hg-rich peculiar stars to evaluate proposed explanations of the observed isotope separation of Hg in the atmospheres of these stars.

Numerous other exciting problems amenable to study with SUOT will be discussed later in this report.

Based on the above considerations, four general observational programs have been given high priority, and will be discussed in detail in Section III. These are:

1. high angular resolution imagery over wide fields;
2. far ultraviolet spectroscopy;
3. precisely calibrated spectrophotometry and spectropolarimetry over a wide wavelength range,
4. solar system studies, including high resolution synoptic imagery.

Other programs considered interesting but not discussed in detail here are: stellar spectroscopy over 1200-3000Å, nebular spectroscopy, broad band photometry including high time resolution studies, near infrared (1-4μm) imagery and spectroscopy, very high resolution (Fabry-Perot) spectroscopy and Michelson interferometry.

Each of the four high priority programs is made feasible by, or at least substantially profits from, the unique flexibility offered by Spacelab. The SUOT will use field correctors to provide a flat field 0.5 degrees in diameter with image diameters of approximately 0.3 arc seconds (60% encircled energy) at wavelengths > 2000Å. Without refractive correctors it will provide similar image quality over a 0.1 degree flat field within the full wavelength range determined by its optical coatings. The full potential of the 0°.5 field may be exploited by large-format electrographs using nuclear track emulsions or by magnetically focused image intensifiers coupled to photographic emulsions. Hypersensitized photographic emulsions without intensification may also be useful for relatively bright targets. The capability to carry large intensifiers or electrographs, to interchange film cassettes by extra-vehicular activity (EVA) on extended flights and to return film to the ground for immediate processing is a unique Spacelab capability which will yield valuable returns in a number of astrophysically important areas.

Neither the International Ultraviolet Explorer (IUE) nor, as presently envisioned, the ST will carry out spectroscopy over the wave length interval 900-1150Å. The primary ST optics will be MgF_2 overcoated and will have poor reflectivity at these wavelengths. Instrument packaging problems and deficiencies in currently available detectors also mitigate against far UV spectroscopy with ST. We recommend that SUOT be capable of periodically flying in a configuration optimized for far-UV observations. The primary and secondary mirrors, which routinely fly with MgF_2 coatings, could be interchanged with carefully protected LiF overcoated optics, or they could be recoated between missions depending on which is more economical. The SUOT facility should be designed for the quick interchange and realignment of optics. With a reasonably high flight frequency and the ability to modify the facility between flights made possible by Spacelab, one need not make a long term commitment to a single telescope/instrument/detector configuration. Relatively high risk detectors, developed in a constantly evolving detector technology, can be used, thus ensuring the greatest possible scientific access to the difficult far-UV region.

The ability to carry onboard calibration sources and to return the SUOT to Earth for postflight calibration will help to ensure high photometric accuracy in the establishment of spectrophotometric standard reference stars sufficiently faint to be of use to ST (bridging the gap between $V = 6$ and $V = 11$ mag.). The same instrumentation will yield high precision (1 percent statistics, 30 minute integration, 10Å bandpass) ultraviolet spectrophotometry on a variety of important targets to $V \sim 16$ mag. or fainter (equivalent unreddened 07 star). Otherwise unobtainable spectrophotometry at wavelengths below 1200Å may be obtained on flights of SUOT carrying LiF overcoated optics.

The opportunities offered by Spacelab for innovative research are well illustrated by SUOT solar system objectives. The SUOT will achieve spatial resolution on Jupiter, for example, equaling or exceeding the best images obtained by Pioneers 10 and 11 (see page 3-24). While ST will be better suited to long term synoptic coverage, SUOT will be able to utilize highly specialized instrumentation suited to specific research objectives, e.g., narrow bandpass interference filters for isolating and mapping particular spectral features over the planetary disc. The SUOT may be the only space telescope usable for near-Sun observations of Mercury, Venus and comets, taking advantage of shadowing by the body of the Shuttle or by a special purpose Sun shield. The SUOT can respond to targets of opportunity - e.g., Martian dust storms and comets of special interest-with instrumentation carefully chosen for specific objectives. We envision that SUOT will carry a high resolution planetary camera on each flight to accommodate synoptic coverage of the planets.

In summary, the SUOT facility will be capable of accommodating a wide variety of specific instrumentation which is tailored to the goals of individual research programs. It will possess a capability for growth and improvement by virtue of interchangeable optics, coatings, focal plane instruments and detectors. It will be amenable to the exploratory use of newly developed detectors. Finally, SUOT should be a highly efficient telescope capable of nearly continuous operation in orbit. This is made possible by the presence of scientists on board who will have the ability to continuously monitor and command the telescope. It is expected that programs and/or instrumentation for use in both the daylight and dark portions of the orbit will be carried on each mission so as to maximize the data return. Thus, although Shuttle flights as long as 30 days are highly desirable, we will show that substantial and important scientific data will be returned from flights as short as 7 days.

III. SCIENTIFIC PROGRAMS

The FDT, as noted above, has chosen the following research programs as the primary areas for emphasis with SUOT:

1. high angular resolution imagery over wide fields,
2. far ultraviolet spectroscopy,
3. precisely calibrated spectrophotometry and spectropolarimetry over a wide wavelength range,
4. planetary studies, including high resolution synoptic imagery.

In this section, we will examine in detail the scientific programs expected to be of special interest, and will give a representative observing program for a 7-day mission in each area in order to illustrate the degree to which significant advances in areas of primary scientific importance can be achieved by even such short missions. In actual practice, it is hoped that most missions will have durations considerably longer than the basic 7-day mission; in any case, it is expected that a mission will usually blend together observations in two or three of these areas.

To insure that the representative observing programs are consistent with one another, the following conventions were adopted:

1. A 7-day mission will allow 6 days of round-the-clock observing. Approximately 96 orbits were assumed available for data collection, and inefficiencies due to South Atlantic Anomaly passages, housekeeping operations, etc., were neglected.
2. Maximum exposure time is 30 minutes. (Actually, in a 450 km orbit any object will be above the horizon for at least 55 minutes each orbit, but the maximum observing time in the Earth's shadow is 35 minutes.)
3. Sky brightness (V) -

ground-based sky	22 mag arcsec^{-2}
night sky in orbit	23 mag arcsec^{-2}
day sky in orbit	20 mag arcsec^{-2}

4. Limiting magnitudes are to be expressed in terms of the visual magnitude of the B0 star which can be observed at the wavelength in question. The B0 flux is that defined by Gingerich and Carbon. Assume reddening to be defined by the Bless and Savage reddening curve.

A. High Angular Resolution Imagery Over Wide Fields

For direct imagery, SUOT's impact will be greatest on problems requiring high resolution over fields significantly larger than the 2.5 arcmin field of the ST f/24 camera. A great many important astrophysical problems fall in this category, ranging from stellar evolution in globular clusters (10-60 arcmin diameter), to the history of star formation in nearby galaxies (12° for the Large Magellanic Cloud, 4° for M31, 34 arcmin for M81, 10 arcmin for the Virgo galaxies), to studies of intergalactic matter in clusters of galaxies (10 arcmin to several degrees for intermediate distance clusters [$z \lesssim 0.1$]). In these areas, SUOT can be expected to function not only as a survey instrument for other space facilities, but also as a primary research tool which will supply definitive information.

A number of programs suitable for SUOT imagery are discussed below. These are based on the expectation (details are given in Appendix B) that in a 30 minute exposure, SUOT will reach V = 25 with S/N = 5 for point sources. These values assume a bandwidth of 1000Å, an overall detection efficiency of 0.1, an image diameter of 0.3 arcsec, and a sky background of V = 23 mag/arcsec^2 in the Earth's shadow. With a 5000Å bandpass, the limiting magnitude for point sources is V = 26.

For many extragalactic problems involving observations in the near infrared or resolution of faint point sources on bright backgrounds, SUOT will have a distinct advantage over any ground-based instrument.

It is also worth noting that in surveys for very faint objects not observable from the ground, SUOT will be much more efficient than ST. For point sources at V = 25, SUOT will reach the same S/N as the presently-envisaged ST, with roughly 11 times the exposure. However, since the SUOT data field is 100 times the area of the ST field, SUOT would survey a large field in the sky to a fixed limiting magnitude in one-ninth the time needed by ST.

1. The Extragalactic Distance Scale

A limiting magnitude of V = 25 and image diameters of 0.3 arcsec would allow SUOT to provide a much more definitive calibration of distance indicators for giant galaxies within 100 Mpc. The primary indicators and the respective distances to which they could be employed are: RR Lyrae stars (600 kpc); Cepheids, brightest Pop II stars and main sequence OB stars (3 Mpc); brightest supergiants in spiral and irregular galaxies (80 Mpc); sizes of HII regions (70 Mpc for 3 pixel coverage); and globular clusters (100 Mpc). Three major clusters of galaxies (Virgo, Pegasus and Perseus) lie within the 100 Mpc limit, and the Coma cluster could be reached with a 1 mag increase in limiting magnitude. For the first time, a truly representative sample of objects with accurate distances will be available to study the nature of the local Hubble flow and to calibrate secondary distance indicators (such as elliptical galaxy core diameters) for use at even greater moduli.

2. Stellar Content of Nearby Galaxies

In addition to the distance criteria cited above, an unprecedented amount of information on the stellar content of nearby galaxies will be available to SUOT. For the first time, the main sequence turnoff in other galaxies will be accessible. Systems nearer than 100 kpc, such as the Magellanic Clouds and the Sculptor dwarf system, can be sampled to $M_V \sim +6$ (see Figure 1). $M_V \sim +1$ can be reached in M31 and its companions; thus, the horizontal branch in all metal-poor dwarf galaxies in the local group can be studied. The distribution of metal content and positional variation of star formation may be studied in detail via individual variable stars and the morphology of field and cluster HR diagrams. Of special interest are star formation rates in the vicinity of spiral shocks derived from observations of hot main sequence stars in spiral galaxies up to 4 Mpc distant. Only the Magellanic Clouds and M31 are significantly larger than the SUOT data field. All smaller galaxies may be surveyed in their entirety to V=25 with 30 to 40 minutes observing time for each wavelength band desired.

3. Deep Sky Imagery

a. Extended regions of galaxies: Very low luminosity extended areas are known to surround (and in some cases interconnect) a number of galaxies. These will undoubtedly shed light on galaxy dynamics and evolution. These extensions may represent a significant fraction of the total galactic mass, and thus may be of interest for cosmology, as well. The ultimate surface brightness limit obtainable with SUOT, assuming multiple exposures and a 2 arcsec image element, is 27-28 mag/arcsec^2. Targets of special interest include halos of edge-on spiral galaxies, rings around Seyfert galaxies, external HI spiral arms without known optical emission, HI "dark companions", interacting galaxies, and elliptical galaxies.

b. Search in selected fields for very distant clusters of galaxies for cosmography. A limiting distance modulus of $\sim$47 is possible for giant ellipticals.

c. Survey selected areas for Quasi Stellar Objects (QSO's) for ST study and for statistical purposes. Ultraviolet or near infrared identification criteria could be used to advantage. At V = 22.5, approximately 40 QSO's should be contained in a single SUOT field.

d. Search in blank radio fields for optical counterparts and in lobes of radio galaxies for luminous matter (typically, 5 arcmin for relatively nearby objects).

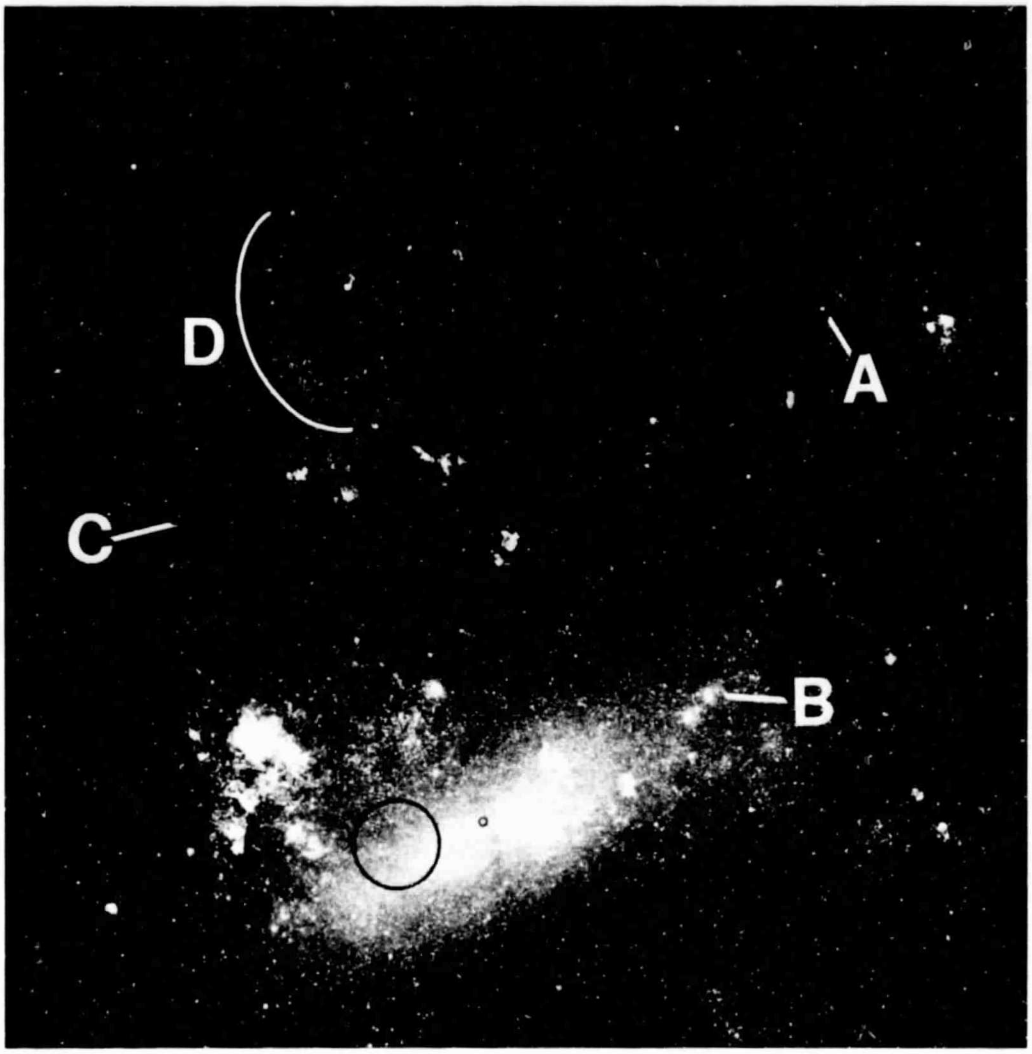


Figure 1. SUOT and Space Telescope (ST) fields of view projected on the Large Magellanic Cloud. This wide-angle photograph (6° X 6°) shows the entire galaxy and illustrates the dense star clusters and star clouds which require the high resolution provided by SUOT if their stellar makeup is to be studied in detail. Objects A and B are examples of the unusual blue globular clusters which occur in the Large Cloud but not in our own galaxy. Object C is a compact cluster embedded in a ring of ionized hydrogen which suggests that one or more stars in the cluster have ejected large quantities of gas. Object D is an arc of early type stars which appears to be almost devoid of hydrogen gas. Detailed studies of the distribution of star types in these and other regions may give new clues concerning the overall pattern of star formation in galaxies.

The smallest images on this photo have a diameter of about 5 arcsec. SUOT image diameters are expected to be 0.3 arcsec. In addition, SUOT will be able to reach much fainter stars than are illustrated on this photograph - V = 25 vs. V = 17. At V = 25 it is possible to study stars with absolute magnitudes of +6.0. This will make it possible to accurately determine the Main Sequence turn off and thus the ages of even the oldest star groups in this galaxy.

The large circle illustrates the area covered by the SUOT field. The small circle illustrates the area covered by the Space Telescope field.

(Photograph courtesy of K. G. Henize and the University of Michigan.)

e. Search for luminous intergalactic matter within clusters of galaxies. Near infrared capability is important to detect low mass stars. Hot gas may be visible in red-shifted Lyman lines. The cores of most clusters of interest are larger than 20 arcmin.

f. Surveys for very low surface brightness dwarf galaxies (thought to be very numerous) in order to determine the faint end of the galaxian luminosity function.

g. Study of spatial fluctuations in the cosmic light -- indicative of object population (including primordial galaxies) at very high redshift. Scales of interest are several arcsec to $\sim$1 arcmin.

4. Structure of Nearby Galaxies

a. High resolution surface photometry of galaxies -- especially, ultraviolet photometry (including selected emission lines) of late-type objects with spiral structure and objects with conspicuous dust lanes.

b. Surveys of nuclear structure, especially for active galaxies (Seyferts, M82, M87, etc.), objects with complex (hot-spot) nuclei, compact galaxies, and objects with dust lane structure near their nuclei. SUOT could extend probable ST coverage here but will offer no particular advantage.

5. Stellar Surveys of Our Galaxy

a. Resolution of the nuclear bulge of our galaxy through gaps in the absorption.

b. Population at galactic poles -- especially hot sub-luminous stars. Color statistics will be useful to the limiting magnitude in determining the structure of the galactic halo.

c. Slitless spectra of selected fields using a prism or grating in the converging beam to derive low resolution (primarily ultraviolet) spectroscopic information for large numbers of objects in the same field.

6. Star Clusters

a. Search for faint members of galactic clusters -- especially, white dwarfs (in order to test supernova models) and lower main sequence stars.

b. Globular clusters: resolution of central regions; large sample color-magnitude diagrams (including ultraviolet colors); luminosity function below turnoff; population of very hot stars. Many globulars can be sampled to $M_V \gtrsim 10$.

7. Interstellar Medium

a. Fine structure in emission nebulae: studies of condensations and filaments in planetary nebulae, condensations and ionization boundaries in HII regions, and structure of supernova remnants (their highly shocked boundaries and hot interiors) through narrow band imagery of optical and ultraviolet emission lines. Wide field imagery will serve in part as a survey for subsequent SUOT (or ST) spectrometry.

b. Fine structure in dust clouds: search for globules, background star counts in direction of clouds, fine structure in dust/gas interaction regions (elephant trunks, etc.), ultraviolet photometry, and polarimetry of reflection nebulae.

8. Special Applications

a. Highest resolution imaging: Since resolution at the f/15 focus will be affected by pixel size of the detector even for pixel diameters of 10μm, the smallest expected in the near future, one can improve SUOT's angular resolution by using transfer optics to expand the plate scale in order to allow several pixels per angular resolution element at a sacrifice in field of view. Several of the programs listed above, such as (4b), (6b) and (7), could benefit from the increased resolution without being severely compromised by the reduction in field. Even though many such problems are high priority programs for the ST, which offers both higher speed and angular resolution, it is anticipated that special aspects of these problems might be more effectively pursued by SUOT. One area in particular is that of planetary imaging, where SUOT may take advantage of special filters, may follow planets closer to the Sun, etc.

b. Ultraviolet polarimetry: Given a nearly linear and highly stable detector, this will be a very interesting application for SUOT imagery. Objects of interest include planets, reflection nebulae, circumstellar clouds, galactic non-thermal sources (such as the Crab Nebula), and dust lanes in galaxies. It is possible that polarization would be a useful identification criterion for faint QSO's.

In formulating a typical observing program we have assumed a launch time near new moon near the autumnal equinox. All exposures are made in the Earth's shadow. Since one such exposure can be made on each orbit, the total number of exposures which may be made in the six operating days of a 7-day mission is 96. We assume an S-20 photocathode operated with 10 filter positions: five broad band filters centered approximately at 0.25 μm, 0.35 μm, 0.45 μm, 0.55 μm, 0.75 μm; two narrow band filters isolating the CIII] λ1908 and C II] λ2326 features; two intermediate band filters isolating regions in the 0.2-0.4 μm range free of common nebular emission lines; and one unfiltered position.

1. M31 region: stellar populations and distance criteria. Two fields: one centered on M32 (including a large fraction of the M31 southern minor axis) and an adjacent M31 field to the southwest, including several spiral arms. One exposure each in the five broad-band filters. Series repeated twice at 1-2 day intervals for variable stars. Total: 30 exposures.

2. M33: spiral structure and stellar populations. Broad band series, emission line filters, one exposure each. Broad band series repeated several days later. Total: 12 exposures.

3. Supernova remnants: ionization/excitation structure in C II, C III ions; ultraviolet non-thermal radiation in Crab Nebula. Two objects are included: S147 and the Crab Nebula. Only part of S147 can be included in the SUOT field. For each object, two exposures in each of the two emission line filters. For the Crab Nebula, two exposures each in the line-free filters. Total: 12 exposures.

4. Interacting and/or radio galaxies: for each object, four exposures without filtration to reach faintest limiting magnitudes on surface areas. Fornax A (main body and one radio lobe) and Stephan's Quartet are appropriate targets. Total: 8 exposures.

5. Clusters of galaxies: for Hubble problem and search for intergalactic matter. For each object, four unfiltered photographs of cluster core for surface photometry, and five broad band exposures for distance criteria. Targets here might be the Perseus cluster (100 Mpc) and the Pegasus cluster (75 Mpc). Total: 18 exposures.

6. South galactic polar survey: three selected fields for stellar population in the halo, QSO's and distant clusters of galaxies. Broad band series for each. Total: 15 exposures.

Thus, with 95 exposures made in the course of 6 days, it will be possible to conduct a high resolution study of the stellar populations of M31, M32 and M33 to $M_V=+1$, to explore at high resolution the structure of two supernova remnants in the light of two ions sensitive to small changes in excitation and ionization, to search for very faint extensions in one radio galaxy and one group of interacting galaxies, to explore two clusters of galaxies for improved distance indicators, intergalactic matter and faint members, and to survey several fields near the south galactic pole for faint blue members of the galactic halo, for QSO's and for new and very distant clusters of galaxies. Since the exposures were confined to the night portions of orbits, at least an equal amount of time is available during the same mission for spectroscopic or planetary studies.

B. Far-Ultraviolet Spectroscopy

Due to instrumentation difficulties, few space telescopes are able to gather data in the astrophysically important 912-1150Å region. In this spectral range it is necessary to avoid all transmission elements, to employ LiF overcoated mirrors, to minimize the number of reflective surfaces and to use only open faced detectors with no transmission elements. The only telescope so far designed to reach this region is OAO-C (Copernicus). Neither ST nor IUE will have this capability. Therefore, it is highly desirable to use the flexibility of SUOT to conduct further studies in this region on one or more missions. In addition to a moderate gain in light-gathering area over that of Copernicus, SUOT can make use of imaging detectors instead of scanning phototubes, which will offer an enormous advantage in the rate of data accumulation.

The scientific programs appropriate to this wavelength region relate primarily to the study of interstellar matter. However, important data on stellar atmospheres also lie in this region as do two problems in solar system spectroscopy. These are discussed below.

1. Interstellar Matter

The ultraviolet region of the spectrum contains most of the important resonance lines from the ground states of common elements, especially for the more predominant levels of ionization expected in space. Also, at low densities, molecular hydrogen can most easily be detected by observing absorptions by the electronic transitions in the far ultraviolet. These were the primary objectives of the Princeton UV telescope-spectrometer, which is operating on OAO-C, and we can best illustrate the important features which lie in the spectral region between 900 and 1150 Å by summarizing important data which were derived exclusively from Copernicus observations in this wavelength range:

(1) Molecular hydrogen Lyman (and Werner) band systems: relative populations in various stages of rotational excitation may be observed. The longest wavelength for a transition from the lowest rotation and vibration level in the Lyman system is 1108Å.

(2) HD molecules: principal lines of the Lyman system start at 1106Å and go shortward.

(3) Atomic deuterium: the Lyman-α (and frequently Lyman-β) interstellar hydrogen lines swamp the accompanying deuterium lines. Hence, the higher members of the Lyman series (at 972Å, 950Å, 938Å, etc.) must be observed.

(4) O VI (1032Å, 1038Å)

(5) N II (1084Å)

(6) C III (977Å)

An example of such data, obtained from Copernicus, is given in Figure 2.

The importance of molecular hydrogen is almost self-evident, in view of its high abundance in dense accumulations of gas and the unexpectedly high degree of rotational excitation which has been found. When compared with the amount of H_2 present and evaluations for the interstellar D/H ratio, measurements of HD give us insight on the rates of ion-molecule exchange reactions in clouds, which in turn are governed by the atomic hydrogen ionization rates.

The ratio of deuterium to hydrogen in the interstellar gas, which reflects upon a universal deuterium abundance, is especially relevant to our estimating the present average density of the universe, if one makes use of the theories of nucleogenesis in the early stages of the primordial explosion. Although there are many other astronomical situations where abundances of deuterium atoms may be sensed, determinations of interstellar atomic D/H ratios provide what is probably the most straightforward measure of the universal ratio. In establishing whether the interstellar ratio is not significantly altered from the primordial value, it would be useful to reach beyond the initial Copernicus results and detect gas at high galactic latitudes which may be somewhat isolated from the material processed through stars (and supernovae) in the disc of the galaxy.

Observations of weak and broad absorption features due to interstellar O VI have established the existence of a tenuous, high-temperature component of the interstellar medium. Absorptions by other highly ionized species, such as S IV, N V and Si IV, do not seem to appear, and this is probably a consequence of the gas being at a temperature in excess of a few times 10^5 °K. Hence, although limited success in registering this gas might result from a very careful search (above 1150Å) for absorptions by N V, Si IV and perhaps C IV, experience up to now suggests O VI may be the only conspicuous tracer. This is an especially important consideration for research by satellites more sensitive than Copernicus, since we could expect to register spectra of stars very distant from the plane of the galaxy and probe the conditions in the galactic halo regions. Our present knowledge of the density, composition, temperature and dynamics of high-temperature gas in the halo is indeed sparse, and additional information here should be valuable in our understanding of

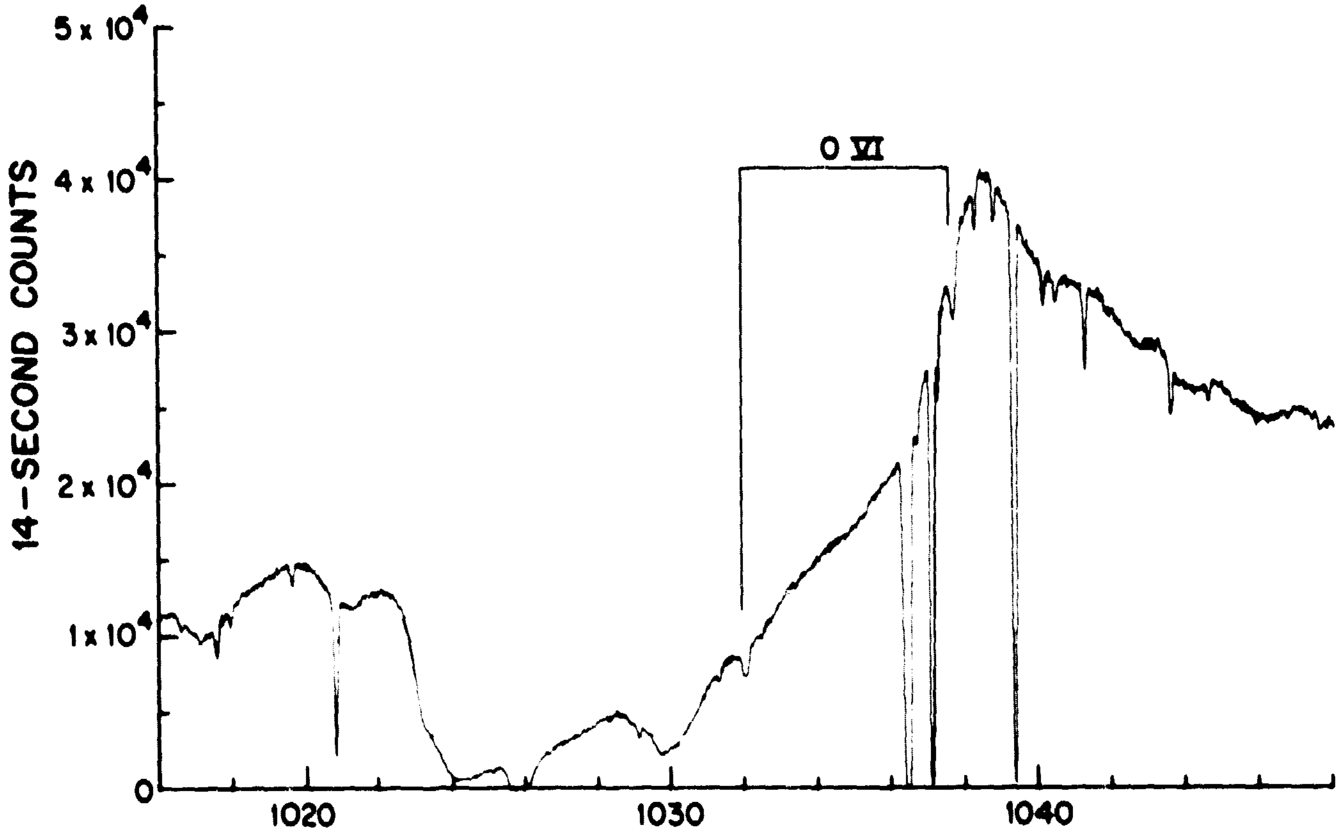


Figure 2. Copernicus spectrum scan of the O5f star ζ Puppis between 1016 and 1048Å. Superposed on the star's broad P-Cygni profile from the O VI resonance lines are sharp interstellar absorptions from Si II (1020.7Å), O VI (1031.9, 1037.6Å), C II (1036.3, 1037.0Å), O I (1039.2Å) and a number of weak absorptions by H_2 in excited rotational levels. The observation shown on this tracing took 21 1/2 hours of Copernicus telescope time to complete; the spectrograph on SUOT could record a complete spectrum of this star from 900 to 1200Å in a single orbit with somewhat better resolution and signal-to-noise ratio. (Note: This figure reproduced by permission from Morton, D.C., 1976, The Astrophysical Journal, Vol. 203, p. 386, published by The University of Chicago Press. Copyrighted 1976 by the American Astronomical Society. All rights reserved.)

galactic structure and evolution. An insight on the distribution of galactic material at large distances is also relevant to a possible explanation for intermediate red-shift lines (from intervening galaxies) appearing in QSO spectra.

Neutral nitrogen atoms have an ionization potential just slightly greater than that of hydrogen. Hence, except for ionization by cosmic rays and x-rays, there should be virtually no production of N II in H I regions. Practically all of the observed N II must arise from H II regions, and this ion serves as an ideal probe, not only for the extent of the ionized zones, but also for the representative electron densities, since absorptions from excited fine-structure levels may be observed.

Another near coincidence of ionization potentials may be found for neutral helium and singly ionized carbon. It follows that C III should be a good indicator for the amount of helium ionization around the stars. Observations of C III by the Copernicus instrument have been somewhat hampered by the relatively low signal and high background levels near 977Å.

Additional benefits for analyzing the interstellar material may result from observations below 1150Å. There are several weak transitions, from such abundant species as Si II (1021Å), N I (964Å) and O I (989Å), which allow us to circumvent difficulties in the interpretation of stronger lines (at longer wavelengths) which are strongly saturated, even for nearby stars.

2. Stellar Atmospheres

It is usually possible to learn much about the structure and composition of the atmospheres of stars by analyzing spectra taken at wavelengths greater than 1150Å. Nonetheless, the shorter wavelengths may often play a significant role in providing data on particular ions whose lines at longer wavelengths may be weak or blended. The peak of the black-body curve occurs near or below 1150Å for the very hot stars, and a study of the spectral behavior near this maximum is crucial, since it is here that the effects of line blanketing are most important in altering the emergent flux. Also, weak lines show their greatest contrast over wavelengths on or below the Planck maximum, since relatively large changes in flux occur for the small temperature differences between the atmospheric levels responsible for the line cores and the adjacent continuum. In the ultraviolet, the wealth of strong resonance lines for highly ionized atoms also contributes some advantage. The discovery of mass loss from the very luminous early-type stars, using rather primitive rocket-borne spectrographs, exemplifies well the new insights which may result from examining short wavelengths. Using a space observatory, one would like to continue studies of P-Cygni type profiles from such ions as C III (977Å), N III (990Å), O VI (1032, 1038Å), P V (1118, 1122Å), S IV (1062Å) and S VI (933, 944Å).

Within its limits of sensitivity (see Appendix C), the Copernicus instrument should permit us to map the properties of a wide selection of stellar types. The IUE telescope will allow the extension of such studies to rarer (and, hence, more distant) or intrinsically fainter stars outside the grasp of Copernicus. However, these two instruments together will not be able to explore the $\lambda < 1150Å$ range for such faint but relatively hot objects as white dwarfs or the central stars in planetary nebulae. A far-UV spectrograph on a 1-meter telescope should open such objects to productive scrutiny. We might also capitalize on the possiblity of examining fainter but hotter companions in binary systems (such as x-ray sources) by observing wavelengths below the primary's black-body cutoff.

3. Solar System Studies

Even though the principal ultraviolet molecular and atomic emission lines occur above 1150Å, there are two problems which must be tackled at shorter wavelengths. First, argon may be an important atmospheric constituent, but its resonance lines occur at 1048 and 1067Å. Second, when studying the emission from the hydrogen envelopes around solar system objects, especially comets, one frequently faces the difficulty that the inner regions are optically deep at Lyman α. A straightforward way of overcoming this problem is to examine radiation from higher terms in the Lyman series, all of which fall below the 1150Å limit.

The following observing program demonstrates the scope of tasks which can be accomplished during a 7-day Shuttle flight. In accord with the scientific objectives outlined above, we shall appropriate observing time among the following areas of research:

(1) Distant stars for interstellar matter research

(2) Highly reddened stars for interstellar matter research

(3) Subdwarf O-type stars

(4) Nuclei of planetary nebulae

(5) X-ray sources with optical identifications

(6) Emission lines from planets

We shall assume that observations may be made both in sunlight and in Earth's shadow and that, on the average, a target is available for 30 minutes per orbit. Although two such observing periods might be achieved in each orbit, we shall assume that the spectrograph is time-sharing with other SUOT instruments. Thus, if we assume that about 96 orbits are available for observation during a 7-day mission, we shall conservatively have 48 hours of actual observing time available.

A list of stars (48) and planets (4) which may be observed during the 48-hours is given in Table 1. This table also lists basic data for each star including $N_S/\sigma(N)$ which is the representative signal/noise ratio expected to be attained on each object in the course of a 30-minute integration time (see Appendix C for the exact definition of $N_S/\sigma(N)$. For all research areas except (2) and (6) above, $N_S/\sigma(N)$ was evaluated for 1030Å. Owing to the steepness in the average interstellar extinction curve at short wavelengths, we can probably record useful spectra for the highly reddened stars only above about 1050Å; hence, $N_S/\sigma(N)$ is quoted for 1100Å.

The signal qualities of planetary observations are gauged by the photoelectrons accumulated over a 30-minute integration time for each Rayleigh of emission. In assigning time for the planets, we shall assume we are fortunate enough to have Lα and other important emission (such as the 1048Å and 1067Å argon lines) appear on the detectors simultaneously, without moving the grating and re-exposing. For each planet the angular size was assumed to be that at mean quadrature or maximum elongation from the Sun. We should recognize, of course, the availability of planets depends very much upon the actual launch date.

Except for groups e and f in Table 1, the general strategy for assigning time is to give each object two observing intervals each of which has a maximum duration of 30-minutes. Those targets which are bright enough to give $N_S/\sigma(N)$ greater than about 100 in a shorter time have their observations curtailed accordingly. Two integrations are generally necessary, since the grating must be moved and the spectrum reobserved to fill in the gaps between the detectors (see Section V.B).

Unfortunately, the signal quality for the highly reddened stars may be rather mediocre - a situation we must tolerate when using far ultraviolet radiation to probe dark interstellar clouds. The observed large variability in extinction at these wavelengths could very well cause these observations to be either of much higher quality or to consist of almost no signal at all.

In summary, we note that the 3-day observing program laid out in Table 1 will provide far-UV spectra (with a photometric precision of 1% in most cases) of 48 stars with a wide variety of astrophysical interest as well as of 4 planets. This program blends well with a direct-imaging program of the kind discussed in Section III. A, both of which may be accomplished during a single 7-day mission.

TABLE 1

OBSERVING PROGRAMS FOR FAR-ULTRAVIOLET (UV) SPECTROGRAPH
(Requires three days of orbital observing time)

a) <u>Distant Stars</u>

HD	V	E(B-V)	Sp	v sin i	log $N_S/\sigma(N)$	ℓ^{II}	r (pc)	z (pc)	Observing Time (min)	Comments
164794	5.97	0.35	O5-O7	168	1.85	6	1200	1025	60	
149881	6.60	0.12	B0.5III	470:	1.58	31	1800	1050	60	behind North Polar Spur
214080	6.80	0.05	B1Ib	102	2.17	45	3000	2500	30	
186994	7.30	0.0(?)	B0III	126	2.35	79	2900	500	15	
219188	6.90	0.12	B0.5III	185	2.09	83	1800	1360	60	
210809	7.55	0.33	O9Ib	114	1.58	100	3400	185	60	
218915	7.20	0.30	O9I	102	1.72	108	3200	-380	60	
14633	7.50	0.10	O8	126	2.09	141	3000	940	30	
41161	6.50	0.17	O9n	300	2.13	165	1400	320	30	
93521	6.90	0.10	O9Vp	303	2.22	183	1900	1700	30	Munch & Zirin show high velocity gas
42088	7.55	0.37	O6	291	1.99	190	2400	+20	60	
52266	7.23	0.30	O9V	303	1.70	219	1700	-20	60	
97991	7.41	0.0	B2V	170	1.99	262	960	+752	60	
99171	6.11	0.11	B0III	240:	2.35	286	1400	+430	15	
86606	6.34	0.10	B1Ib	300:	2.15	290	2200	-505	30	
112244	5.40	0.32	O9Ib	138	2.03	304	1300	130	60	
135591	5.50	0.19	O9I	131	2.29	320	1700	-75	15	
150898	5.57	0.13	B0Iab	108	2.42	330	1900	-280	7	
1550806	5.50	0.30	O8e	211	2.05	353	1450	70	60	
								Total	13.4 hours	

NOTE: Stars are listed in order of increasing galactic longitude, ℓ^{II}.

Table 1 (Cont.)

b) Highly Reddened Stars

HD	V	E(B-V)	Sp	v sin i	log $N_S/\sigma(N)$	r (pc)	E(B-V)/r* (mag kpc^{-1})	Observing time (min)	Comments
147889	7.86	1.10	B2V	100	0.30	260	4.26	60	
167971	7.52	1.05	07.5If		0.54	1400	0.74	60	
169454	6.61	1.13	B1Ia		0.59	900	1.23	60	
194279	7.01	1.20	B1.5Ia		0.39	1050	1.14	60	
194839	7.50	1.18	B0.5Ia	79	0.33	1200	1.00	60	
195592	7.08	1.14	09.5Ia	79	0.48	1200	0.97	60	
							Total	6 hours	

*A general average of E(B-V)/r in our part of the galaxy is 0.61 mag kpc^{-1}.

c) sdO Stars

ID	V	E(B-V)*	log $N_S/\sigma(N)$	Observing Time (min)
BD+75^{o}325	9.2	0.10	1.77	60
F 34	11.21	0.10	1.36	60
F 66	10.54	0.12	1.46	60
F 67	11.86	0.06	1.32	60
HZ 44	11.71	0.13	1.20	60
HD127493	8.54	0.61	0.86	60
BD +33^{o} 2642	10.84	0.23	1.17	60
BD +28^{o} 4211	10.2	0.06	1.65	60
			Total	8 hours

*Intrinsic colors assumed to be $(B-V)_o$ = -0.40

Table 1 (Cont.)

d) Planetary Nebula Nuclei

Nebula	V	E(B-V)	log $N_S/\sigma(N)$	Observing Time (min)
NGC40	11.64	0.35	0.77	60
NGC1535	11.92	0.20	1.02	60
IC418	9.37	0.24	1.45	60
A36	11.55	0.22	1.05	60
NGC6543	10.39	0.30	1.12	60
NGC6826	10.48	0.19	1.33	60
NGC7009	11.5	0.0	1.51	60
NGC246	11.95	0.03	1.36	60
NGC3242	12.03	0.17	1.06	60
NGC7662	11.80	0.15	1.14	60
NGC2392	10.43	0.16	1.40	60
			Total	11 hours

e) Binary X-ray Sources

HD	Source	V	E(B-V)	Sp	log $N_S/\sigma(N)$	Observing Time* (min)
77581	3U0900-40	6.88	0.78	B0.5Ib	0.84	90
153919	3U1700-37	6.55	0.6	07f	1.28	90
24534	X Per	6.35	0.56	09.5 ep	1.40	90
					Total	4.5 hours

*Consists of many short observations at various phases of the orbit.

f) Planets

Planet	30 min counts/R_o at 1216Å	30 min counts/R_o at 1050Å	Observing Time (min)
Venus	0.47	1.3	30
Mars	0.16	0.43	30
Jupiter	0.74	2.0	60
Saturn	0.34	0.92	120
		Total	4 hours

C. Precisely Calibrated Spectrophotometry

Absolutely calibrated spectrophotometry is of fundamental interest to almost every area of astrophysics and cosmology. Space-based telescopes have unique advantages in making such measures, not only because they have access to the entire electromagnetic spectrum, but also because they avoid the time-variable, wavelength-dependent absorption problems of the earth's atmosphere. The SUOT will be the first 1-meter class space telescope with adequate calibration control to extend such measures to moderately faint stars.

Absolute calibrations of stellar spectral energy distributions have been carried out with fully calibrated small instruments in sounding rockets, and will be conducted with small shuttle payloads for bright stars via techniques such as the synchrotron method of Bless, Code, and Fairchild. However, the objects which can be measured with high precision by small, absolutely calibrated instruments are far too bright for large instruments such as the ST to observe without severe overloading of counters. By analogy, the Oke multichannel scanner on the Palomar 5-meter and the Wampler IDS on the Lick 3-meter are restricted to objects fainter than about V = 10.0, while instruments with apertures of the order of 30 centimeters can produce high-precision data in reasonable times only for objects brighter than perhaps V = 7. The SUOT spectrophotometer will be able to bridge this gap to establish a sequence of ultraviolet standards for the ST. For this reason alone, SUOT will be an extremely valuable, if not crucial, element in the fundamental problem of absolutely calibrated spectrophotometry.

In addition to the above ST service function, the SUOT spectrophotometers will be able to address directly numerous problems of great interest. For example, bolometric luminosities of hot stars are important for numerous problems, but are still poorly known. Of special import in this context are the strong absorptions in the ultraviolet by abundant atomic species such as carbon. The SUOT spectrophotometer will be able to measure the complete spectrum, with high photometric precision, of a wide variety of stars of all population types, and thereby provide empirical bolometric magnitudes. These would be particularly important for the understanding of Population II stellar atmospheres; for instance, the blue horizontal branch stars in globular clusters which could be reached and isolated by the facility. Such observations in a vastly expanded sample will serve further to refine the understanding of the influence of departures from LTE and from static, plane-parallel atmospheres.

The Copernicus observation of the depletion of heavy elements in the interstellar gas makes the extension of the extinction curve determinations begun by OAO-2 (and the inclusion of polarimetric information in those determinations) of great importance, since these data can place important constraints on the grain composition. This is particularly the case across the 2200Å feature seen in Figure D-1 of Appendix D, which is suggestive of graphite, and also at shorter wavelengths where the rapid increase is believed by Witt and Lillie to be due to scattering. This latter conclusion is further reinforced by the requirements on grain albedo below the Lyman limit which Mezger, et al., impose in order to explain the relative ionizations of hydrogen and helium in H II regions. The SUOT would be able to measure the ultraviolet extinction curves for the complexes of stars within H II regions, such as the Trapezium and the several stars which are collectively know as HD 164492 in NGC 6514. These stars are known to have anomalous visual extinction curves, which are presumably due to the hostile environment within the nebula. OAO-2 observations suggest effects in the 2200Å feature, but the accurate elimination of the nebular scattered light and the separation of the individual stars was not possible with the OAO, but would be with the SUOT. This separation would further help to resolve the degree of circumstellar contribution to the anomaly.

Among the many extragalactic problems which might be addressed by the SUOT spectrophotometer, an excellent example is the discrimination between the various models proposed to explain the spectra of Seyfert galaxy nuclei. The relative importance of early-type stars and interstellar dust in galactic nuclei could also be determined by SUOT. Its angular resolution would be crucial in separating nuclear regions from other parts of the galaxy. Ultraviolet spectrophotometry of QSO's with intermediate redshifts would detect the same lines observed in optical wavelengths in high redshift objects. High-precision spectrophotometry of all of the emission lines in such QSO spectra would serve to define more accurately the physical conditions in these most interesting objects. In summary, the overall importance of spectrophotometric data argues strongly for the inclusion of such instrumentation on several SUOT missions.

To delineate a typical observing program, we assume two 30 minute exposures per orbit, this giving a total of 192 exposures. Not all exposures will need to utilize the full 30 minutes; indeed, many would be substantially shorter. On the other hand, some windows will be lost to the South Atlantic Anomaly when high voltages must be turned off, and some will be lost to target identification problems, rest periods, maintenance, and other slippage. Thus, as a typical figure, we will adopt a norm of 180 exposures per mission.

A single such mission would probably suffice for the establishment of the sequence of faint spectrophotometric standards discussed above. For this purpose, we will assume that on each target four separate exposures must be taken, one each for each of the grating-blaze/detector combinations required to cover the spectrum from 912Å to 10,000+Å (see Section V-C). If the sequence of absolutely calibrated bright standards consisted of the 12 stars of the Hayes (1970) system, the four exposures could be made during a single orbit window on each object. However, each primary standard should be observed an average of three times during the mission (beginning, middle, and end) to monitor stability. Thus standardization would consume a total of 36 windows, which leaves 144 windows for program stars. If each of the program stars requires either a full window per wavelength region, or if, for the brighter ones, multiple observations are anticipated, then we could observe 36 sources. such as all of the faint standards in the list of Stone (1974) and all of the bluer white dwarfs in the list of Oke (1974). The result would be an internally consistent system of approximately 30 spectrophotometric standards well distributed over the sky, representing a dynamic range of more than 100 and calibrated from the Lyman limit to the redmost capability of photomultipliers -- a most worthy project.

On subsequent missions not dedicated solely to calibration, it should be anticipated that on the order of 30 windows would be allocated to the calibration of that flight and the rechecking of selected standards. This would leave approximately 150 windows for other programs of spectrophotometry. Again allotting four windows per object, with some allowance for false starts and reobservation, approximately 30 sources per mission could be observed. This number would represent a substantial sample for any of the programs previously discussed. The extension of the missions to two weeks or a month would more than double or quadruple this productivity, since the fractional allocation of time devoted to standardization would decrease. A single 30-day mission would probably suffice to measure virtually all of the unusual objects in the list of faint blue stars at high galactic latitude of Greenstein and Sargent (1974). A 2-week mission would allow us to observe all the extragalactic objects in Table 2. Clearly, a very substantial amount of important research can be done within the time constraints of expected Shuttle missions.

D. Solar System Studies

High resolution and accessibility to the IR and UV regions of the spectrum, and the ability to observe at small solar elongation angles will make SUOT a valuable tool for the study of solar system objects, including planets, satellites and comets. Also, the ability to monitor transient phenomena almost continuously over periods of 1 to 4 weeks gives SUOT another important advantage over ground-based telescopes.

TABLE 2

EXTRAGALACTIC SPECTROPHOTOMETRIC TARGETS OBSERVABLE IN A TWO WEEK FLIGHT

a) SOME BRIGHT QSO's

Name	V	B-V	U-B	Z	Polarization	Comments
3C 273	12.8	+0.21	-0.85	0.158	?	
PKS 1004+13	15.15	+0.13	-	0.240	-	
PKS 1302-102	15.25	-0.05	-0.82	-	-	
3C 351	15.28	+0.13	-0.75	0.371	-	
PKS 2135-14	15.53	+0.10	-0.83	0.200	-	
3C 249.1	15.72	-0.02	-0.77	0.311	-	
PKS 0837-12	15.76	+0.02	-	0.200	-	
TON 469	15.78	+0.10	-0.68	0.534	-	
3C 323.1	(15.8)	-	-	0.264	-	
PKS 2251+11	15.82	+0.20	-0.84	0.323	-	
TON 256	15.91	+0.57	-0.84	0.131	-	
PKS 2344+09	15.97	+0.25	-0.60	0.677	-	
PKS 2128-12	15.98	+0.13	-0.67	-	-	
Markarian 132	16.00	+0.25	-0.84	1.758	-	
BL Lac	12.0-15.6	+0.99	-0.14	0.07?	2-10%	
PKS 0537-441	12.6-16.5	-	-	-	-	
OJ 287	13.1-13.8	-	-	-	2-15%	Like BL Lac
3C 345	14 -18	+0.29	-0.50	0.594	2-10%	
PKS 0735+178	14 (var)	+0.52	-0.43	0.424	2-30%	
PKS 1400+162	14 (var)	-	-	-	5-10%	Like BL Lac
3C 66A	15.21	+0.50	-0.49	-	-	Like BL Lac

Table 2 (Cont.)

b) BRIGHT SEYFERT GALAXIES

NAME	m_{TOTAL}	$m_{NUCLEAR}$	B-V	DIAMETER	Z
1068	9.81	-	0.74	380"	0.004
1275	13.14	-	0.85	68"	0.018
1566	10.09	-	0.70	-	0.004
3227	11.75	-	0.87	330"	0.003
3516	12.86	14.0 - 15.0	0.79	80"	0.009
3783	(13 08)	-	0.56	72"	0.009
4051	11.23	14.6	0.65	280"	0.002
4151	11.48	12.2 - 13.4	0.74	450"	0.003
5548	13.54	14.7 - 15.7	0.60	80"	0.017
6814	12.46	-	0.89	136"	0.005
7469	13.06	14.7 - 15.5	0.67	89"	0.017
7603	14.01	-	0.72	55"	0.029
Mk 501	13.88	-	0.72	60"	0.033
Mk 3	13.34	-	1.15	44"	0.014
Mk 231	13.84	-	0.84	27"	0.041
Mk 335	13.85	-	0.41	16"	0.025
3C 120	14.27	-	0.58	42"	0.033

Even though ST may also be used to observe solar system objects and will have the advantage of higher resolution and greater aperture, it is likely that specialized equipment, such as polarimeters and medium-and narrow-band filters (tuned, for example, to isolate methane and ammonia absorption bands, sodium D lines or spectral absorption features of minerals), will not be available on ST. Likewise, the presence of men with SUOT makes possible delicate and rapid maneuvering of both Shuttle and SUOT, which will permit observation of planets and comets at much smaller elongation angles than ST can tolerate. For example, it is expected that Mercury at elongation may be observed during the 5-minute period between its rise and the rise of the Sun, and that SUOT may then be repointed before any significant thermal stress occurs in the telescope optical system. The presence of man also makes possible quicker detection and better tracking of transient phenomena.

It is recommended that a very high resolution planetary camera be carried on every SUOT flight in order that synoptic photography may be carried out as often as possible. Since exposures on planets will be short, it is expected that relatively little observing time will be required to accumulate significant amounts of synoptic data on all the planets. It is expected that this camera will use all-reflecting transfer optics to maintain broad spectral response, and will be designed to ensure that resolution will be diffraction limited and not detector limited. The resulting 0.1 arcsecond resolution at 4000Å translates to a linear resolution of 75 kilometers at a distance of 1 AU. By use of image processing, it is possible to make further improvement in resolution at some expense to photometric fidelity.

Although high resolution direct imaging would be the primary solar system observing program, extremely valuable spectrophotometric data could also be obtained by use of the spectrographs and spectrophotometers which are also expected to be available with SUOT.

The following sections indicate, on a planet-by-planet basis, the scientific problems on which SUOT data would have a significant bearing.

1. Direct Imaging Programs

Mercury. Resolution: approximately 75 km. Medium-passband spectrophotometry and polarimetry would aid in the mapping of distinct geological provinces. At this resolution, it would not be possible to detect individual topographic features. Significant improvements in our knowledge of both the figure and obliquity of Mercury could be made.

Venus. Resolution: 50 to 100 km. Observations of the 100 m/s UV clouds would lead to a better understanding of zonal and meridional motions than has been acquired so far through Mariner 10 and ground-based imaging. Although the Mariner 10 photography has been very valuable in providing clues to the planet's atmospheric circulation, the interval of observation was less than 10 days and, therefore, represents only a momentary look at an atmosphere which ground-based photography suggests is constantly changing. The ability of Pioneer Venus Orbiter 1978 to provide imaging of UV clouds at sufficiently short time intervals is presently open to question.

Spectrophotometry and polarimetry at high angular resolution from the visible to vacuum ultraviolet regions of the spectrum should lead to positive identification of the composition and size distribution of cloud particles, and bring out any differences between the bright and dark ultraviolet clouds. The recent identification of bright cloud particles as uniform droplets of concentrated H_2SO_4 is not completely consistent with the observations.

Mars. Resolution: 30 to 150 km. Narrow-band filters would permit the monitoring of the time-dependent, spatial distribution of minor atmospheric constituents such as CO and O_3, important to studies of Martian aeronomy.

Observations of the initial stages of Martian dust storms would help to determine the conditions that cause them. Both continuity and high resolution in several spectral passbands are important. The Martian date of onset of major dust storms is usually predictable within a few weeks.

The association of the diurnally and seasonally variable, discrete white clouds with large Martian volcanos is now well established. However, the details of day-to-day variations in cloud intensity and the precise locations of the clouds with respect to the individual volcanic summits is very poorly known. Detailed knowledge of this behavior would aid in determining whether the clouds are caused by orographic uplift or by local-source degassing, possibly associated with volcanic activity. Blue-light imaging at appropriate time intervals during the Martian season of maximum white cloud activity would provide such knowledge.

Jupiter. Resolution: 300 to 450 km. SUOT imaging with resolution comparable to or better than the best obtained by Pioneers 10 and 11 can be achieved (see Figure 3). Mariner Jupiter/ Saturn 1977 will obtain photographs with resolution better than 300 kilometers for only 25 days out of a scheduled observing interval of 80 days.

Synoptic imaging at regular intervals over a 10-day time base

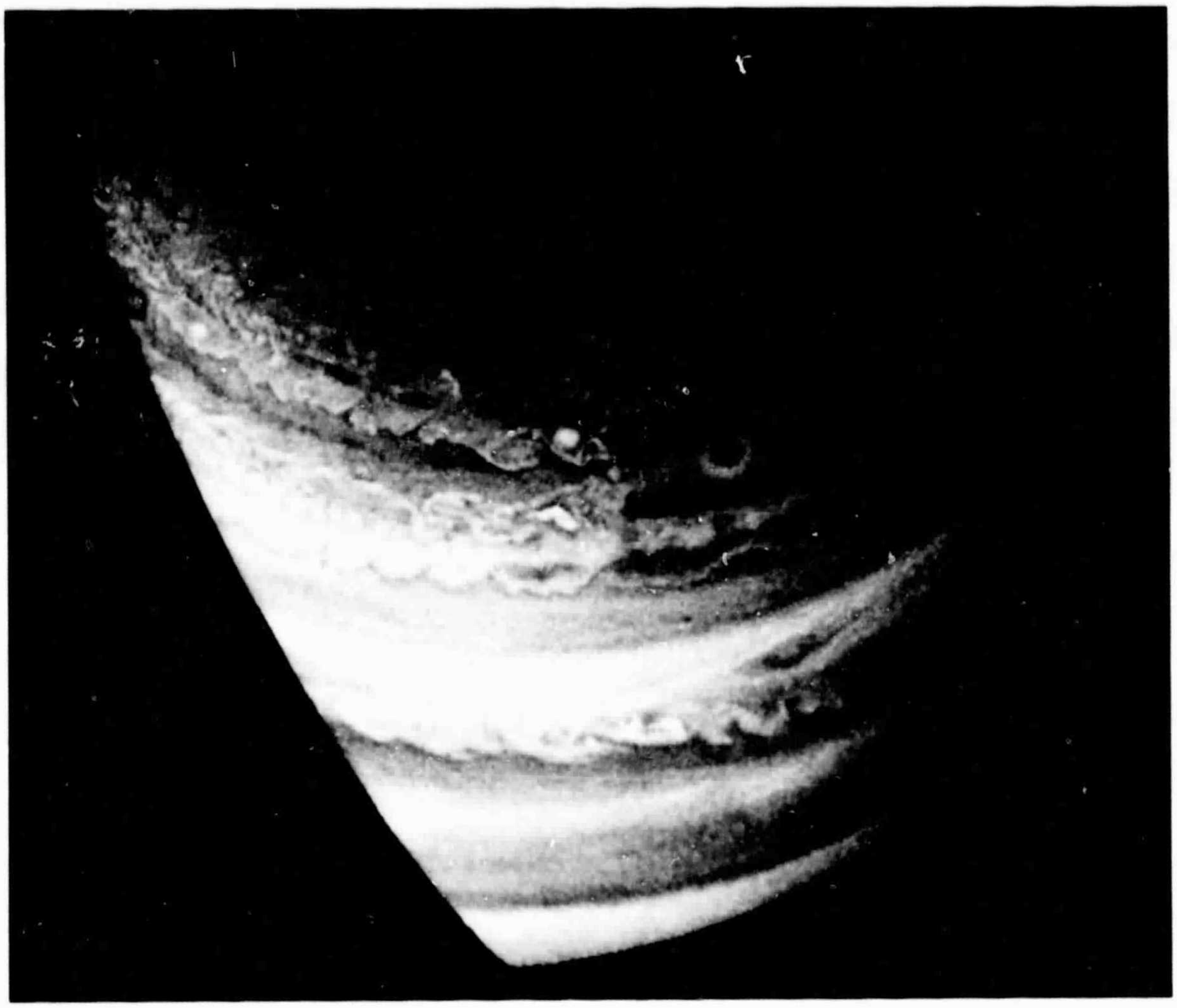


Figure 3. Pioneer 11 high resolution image of Jupiter in blue light, as observed at a distance of 609,000 km on 3 December 1974. The limiting linear resolution in this view is somewhat greater than 300 km. The excellent image quality provided by SUOT will allow spatial resolution on Jupiter from earth orbit equaling or exceeding that achieved by Pioneer 10 and 11. The flexibility of Spacelab operations will allow the use of instrumentation designed for specific research goals - e.g., narrow band interference filters to isolate and map specific spectral features. The FDT recommends that a planetary camera be carried on each flight of the SUOT to provide regular synoptic coverage (Photograph courtesy of Dr. Tom Gehrels, University of Arizona.)

can obtain the zonal and meridional components of the Jovian wind field with mean velocity errors of less than 0.2 m/s. Observations of the Jovian wind field at the visible cloud surface, when combined with high resolution cloud morphology, could lead to a better understanding of the planet's general circulation. It should be noted that the MJS77 mission can provide even better information on the motions and morphology of small scale cloud features. However, like the Earth, Jupiter undergoes large changes in cloud structure and flow patterns over periods of hundreds to thousands of days. Thus, SUOT observations would tend to complement rather than duplicate results obtained from non-orbiting planetary spacecraft.

All of the comments which apply to the study of cloud motions in general apply equally well to the study of features of special interest, such as the Great Red Spot, South Equatorial Belt disturbances and the North Temperate Belt (southern component) zonal jet. The activity associated with these and various other interesting atmospheric phenomena is often ephemeral in nature, and can easily be missed during the short time interval of near encounter in a fly-by mission.

As with cloud motions, planetary spacecraft are better suited than the SUOT or the ST to make limb darkening measurements, not only because of the ability of the planetary spacecraft to obtain higher spatial resolution, but also because of their unique viewing geometry. However, the cloud structure and its scattering properties are undoubtly time variable, and SUOT studies would again tend to complement those results obtained from planetary spacecraft.

High resolution imaging of Jupiter in the 8900Å absorption band of CH_4 would provide useful information on individual cloud heights. Similar photography in the 2200Å absorption band of NH_3 would give the planet-wide distribution of ammonia in the Jovian upper atmosphere. The response of the vidicons which will fly on MJS77 is such that neither of these bands can be observed.

Imaging of Jupiter at wavelengths shortward of 300 nm would give the temporal and spatial distribution of ultraviolet absorbing aerosols in an otherwise Rayleigh scattering atmosphere. The shortest wavelength at which MJS77 pictures can be taken is about 3000Å, although the MJS photopolarimeter can obtain line scans down to approximately 1800Å.

Saturn. Resolution: approximately 650 km. Most of the science objectives which are given for Jupiter apply equally well to Saturn. Mean errors associated with cloud motions will be approximately twice as large for Saturn.

There is little that the SUOT could do with the rings of Saturn that could not be done better by Pioneer 11 or MJS77, unless a SUOT Shuttle flight could be scheduled as early as 1980, when the earth passes through the Saturnian ring plane. Such observations would establish the amount of material which may exist within the ring plane, but situated either radially outside and/or inside of the visible rings.

Uranus. Resolution: 1500 km. Only tenuous cloud markings have been photographed on Uranus. A search for detailed cloud structure followed by persistent observations is important because discrete features would provide the first accurate value of the planet's rotation period. Limb darkening curves, superior to those obtained by flight 7 of Stratoscope II could be produced from deconvoluted SUOT imaging.

Neptune. Resolution: 2200 km. The science objectives given for Uranus apply to Neptune as well.

Pluto. Resolution: 3000 km. It is doubtful that SUOT imaging of Pluto would produce results of value.

Satellites. Resolution: Identical to that of their primaries. In general, imaging of satellites would produce data that are appreciably inferior to those obtainable by planetary spacecraft. An exception would be Titan, where observations of its time-variable atmospheric cloud cover would complement Pioneer 11 and MJS77 imaging results.

2. Spectroscopic Programs

Useful spectroscopy can be done by SUOT at both ultraviolet and infrared wavelengths. Ultraviolet spectroscopy would give the distribution of hydrogen around Jupiter, Saturn, Io and Titan, as well as its isotopic abundances (H/D) at H Lα and D Lα. Argon in the Martian atmosphere could be estimated from the strengths of the resonance lines at 1048Å and 1067Å.

Electronic transitions in biologically important organic molecules occur in the spectral region from 2000Å to 3000Å. A search in the atmospheres of Jupiter, Saturn and Titan for such molecules would be a crucial step in determining whether or not chemical or biological evolution of organic molecules has taken place on these outer solar system bodies.

The precisely calibrated spectrophotometer (PCS) will be useful for planetary studies. For example, its high angular resolution makes possible the measurement of UV albedos of small surface regions of nearby planets. These observations could be carried out synoptically with an efficiency nearly equal to that of the ST, since the detection of surface brightness depends only upon the f-ratio of the system. This factor is comparable between the two facilities, while the angular resolution superiority of the ST is only a factor of two or three greater, and may, in this context, be unnecessary. Furthermore, the presence of the observer might be the best way to insure the acquisition and tracking of moving and transient features such as Martian dust clouds. The PCS should also be particularly well suited to high precision spectro-polarimetry of planetary atmospheres with high angular resolution.

Although Fourier spectroscopy of the planets in the near infrared (1 to 4 μm) can be accomplished from the NASA C141 infrared observatory, it is found that angular resolution is quite poor due primarily to turbulent air flow over the observing window. Therefore, high angular resolution IR spectroscopy from SUOT will be highly desirable.

It is unlikely that a 7-day SUOT mission would be dedicated entirely to solar system observations. Therefore, we have not formulated such an observing program, but, instead, have itemized a "typical" planetary direct imaging observing program which might be carried out daily during a SUOT mission.

We assume two filter wheels, one containing four polarizers and a clear aperture, the other, approximately eight color filters. As an example, the color filters might include four broad-band (500Å bandpass) filters centered at 2500, 4500, 6500 and 8500Å and four narrow-band filters isolating prominent bands of methane, ammonia, ozone and pyroxene. It is further assumed that an observation of the five bright planets with a broad-band filter requires roughly 1 minute* and that an observation through a narrow-band filter requires roughly 2 minutes.

If we assume that each bright planet will be observed once every 24 hours with two of the narrow-band filters, with each broad-band filter by itself and, finally, with the 4500Å filter and each of the polarizers, we arrive at an observing time of 12 minutes per planet. Thus, observing all five bright planets once each day would require roughly 90 minutes (60 minutes plus maneuvering and set up time), i.e., about 6% of the total observing time. Similar observations of Uranus and Neptune will require considerably longer observing periods, but would presumably be carried out less frequently.

---

* This time includes operational set up time and also envisions multiple exposures. Actual exposure times should be a fraction of a second for wide band filters. For example, if the planetary camera operates at f/60 and has a 10% quantum efficiency, the exposure for a 500Å bandpass should be about 10^{-2} seconds for Venus, 10^{-1} seconds for Mars and 0.5 seconds for Jupiter. These exposures are sufficiently short to prevent loss of resolution due to motion of the planet relative to guide stars.

E. Other Programs

In addition to the above highest priority programs, the FDT also noted several areas of research which will be of obvious interest to SUOT users. These include moderate resolution spectroscopy at wavelengths from 1200Å to 8000Å; infrared Fourier spectroscopy from 1 to 4 μm; wide field, high angular resolution (nebular) spectroscopy: and filter photometry. With man's presence it may be possible also to employ complex, high-risk instruments such as a very high wavelength resolution Fabry-Perot spectrometer or a Michelson beam interferometer for measuring stellar diameters.

Even though at first sight some of these appear to strongly overlap the scientific objectives of ST instruments, it should not be forgotten that SUOT instruments have a degree of flexibility not available to ST. Thus, exotic detectors, new varieties of filters and gratings, new data handling methods, etc., may be accommodated by SUOT from mission to mission. And, in many cases, SUOT is able to observe more efficiently in the intermediate magnitude ranges too faint to be reached by IUE but too bright to be efficiently handled by the ST detectors.

The moderate resolution spectrograph would most likely be an echelle system giving a wavelength resolution in the 0.1Å to 1Å range. Its design should emphasize high efficiency rather than high photometric accuracy, so that stars in the 8th to 15th magnitude range could be observed with reasonable exposures. The scientific programs which it would accommodate include the following: abundance studies of horizontal branch stars in globular clusters and the galactic halo, abundance versus luminosity and position studies of blue giants and supergiants in the Magellanic Clouds, spectroscopy of components of close binary stars, studies of the ultraviolet spectra of old novae, dwarf novae and flare stars, ultraviolet studies of magnetic variables and peculiar A stars, etc. Scaling from study results for ST, we estimate the following limiting magnitudes for spectroscopy in the visible (corresponding limits for ultraviolet spectroscopy are a function of spectral type). These assume a 1Å match to a single 30 μm pixel, an overall system efficiency of 1% and a 10^4 seconds integration time.

Standard Deviation	Limiting V Magnitude
10%	18.4
5	17.0
3	15.9

Nebular spectroscopy can benefit from the extended wavelength range, high resolution and comparatively large field provided by the SUOT. A program of prime interest with such an instrument would be the study of ultraviolet emission from supernova remnants. Lines of special interest are included in Table 3.

Although x-ray emission is more useful in studying the physical nature of very young remnants, ultraviolet and optical lines are very useful in studying the older and cooler remnants. As an example of the value of ultraviolet data, we can measure line ratios of transitions which occur in the same ion. Thus the ratio of the total flux in the [Ne IV] 1609Å, 1608Å lines to the total flux in the [Ne IV] 2441Å, 2438Å lines is a measure of the temperature of the gas in which the ions are located. The line ratio of the [Ne V] 1575Å and the [Ne V] 3346Å, 3426Å lines yields similar information. On the other hand, the ratio of the flux in the [Ne IV] 2441Å line to that in the [Ne IV] 2438Å line is a sensitive indicator of the gas density. In the far ultraviolet, two of the most important lines which should be looked for are O VI 1031Å and [Ne VI] 1060Å, which are formed at intermediate temperatures, 3.2 to 5 x 10^5°K, and are comparatively strong.

It is also important to determine ionic abundances, in order to accurately understand the details of the shockwave theory and the overall heating effect of the supernova on the interstellar medium.

Crucial to these measurements is knowledge of the interstellar extinction between the remnant and the observer. Intensity ratios between auroral and transauroral lines are useful for this purpose. Examples of such ratios are [O III] 2321Å, 2332Å/ [O III] 4363Å; [Ne V] 1562Å, 1574Å, 1592Å/ [Ne V] 2975Å; [Ne IV] 1609Å/ [Ne IV] 4715Å, 4725Å; [O II] 2470Å/ [O II] 7319Å, 7330Å; [N II] 3063Å, 3070Å/ [N II] 5754Å; [Ca V] 2412Å/ [Ca V] 3996Å. Ideally, this information would be supplemented by photometry of hot stars in the neighborhood of the remnant.

When equipped with a Fourier spectrometer and semi-conductor detectors, SUOT should be a powerful tool for studying the spectra of stars and planets in the 1-4 μm region. Even though similar studies can be conducted from balloons or the NASA C141 Infrared Observatory, SUOT will have the advantage of greater angular resolution and reduced background radiation.

Absolute infrared spectrophotometry should be particularly valuable in improving our knowledge of the bolometric radiation of cool stars and in determining opacity sources, relative abundances of atomic and molecular species and the physical conditions in the outer layers of the photosphere. In the 1 to 2 μm region, absolute spectrophotometry of selected standard stars would not only provide useful data for refining model atmospheres for cool stars, but would also provide standards useful to both the ST and the Shuttle Infrared Telescope (SIRTF).

TABLE 3

SPECTRAL LINES OF SPECIAL INTEREST
IN SUPERNOVAE REMNANTS

Line Identification	Emissivity Per Hydrogen Atom (10^{-23} Ergs cm^{-3} s^{-1})	T max (10^5°K)
C II 1334	3.34	0.5
C III 977	15.8	0.8
C IV 1550	5.49	1
N III 992	1.70	1
O VI 1031	7.7	3.2
Ne VI] 1060	0.80	5
O IV] 1406	2.94	1.6
N III] 1750	0.87	0.8
Si III] 1885	0.53	0.63
Si III] 1892	0.34	0.63
C III] 1906	2.88	0.8
C III] 1909	1.91	0.8
C II] 2326	3.68	0.4
[Ne IV] 1609	0.318	1.6
[Ne IV] 2440	1.22	1.6
[Ne IV] 2438		
[Ne V] 3346	0.377	3.0
[Ne V] 3426	0.377	3.0
[Ne V] 2972		3.0
[Ne V] 1575		3.0
[O II] 3726	1.23	0.4
[O II] 3729	1.79	0.4
[Ne III] 3869	0.522	1.0
[Ne III] 3968	0.522	1.0
[O III] 4959	0.403	1.0
[O III] 5007	1.17	1.0
[Si VIII] 2764	5.3	9.3

Preliminary calculations show that SUOT should obtain data in the 1 to 2 μm region with a S/N of 30 and a resolving power of 2000 on 5th magnitude M0 stars.

Filter photometry is an obvious general purpose application of any telescope. By sacrificing spectral resolution, broad band photometry is able to provide greater photometric accuracy, and can reach much fainter stars or finer time resolutions than available from spectrophotometry. It is probable that scientific programs for such an instrument as SUOT would include high-accuracy ultraviolet photometry of barely resolved globular cluster stars and binary stars, refined follow up color data on newly discovered blue halo stars, QSO's, etc., and rapid photometry over a wide wavelength range of QSO's, pulsars, rapid variable stars, and planetary and lunar occultations of stars and satellites.

IV. FACILITY CONCEPT AND SPECIFICATIONS

A. Basic Concepts and Specifications

The basic concept for SUOT is generally defined by the guidelines presented to the FDT. These are listed in Appendix A. The FDT found these guidelines reasonable, although it was noted that cost considerations (Item 6) could not be dealt with by the FDT directly. The basic mechanical and optical features and specifications arrived at by the FDT are summarized in Table 4.

B. Pallet-Mounted versus Accessible Focal Plane Configuration

The FDT considered the option of mounting the telescope externally on a Spacelab pallet versus mounting it in a way so that the focal plane is delivered into a pressurized Spacelab module. We noted that the accessible focal plane would give direct access to instrumentation, thus allowing a greater number of and more detailed adjustments to complex instruments, greater ability to troubleshoot and repair malfunctioning instruments, unlimited scope for exchanging instruments, and greater flexibility in retrieving film and exchanging film magazines. However, opposing arguments included the likelihood that use of a pressurized module would prohibit missions as long as 30 days, that costs might be prohibitively large if extensive modifications to the module were required, and that the module might curtail the ability to share payload volume and mass with other payloads. A compelling scientific argument against the accessible focal plane concept (AFPC) is its requirement for a tertiary diagonal mirror, which is objectionable both for experiments which wish to minimize reflections in order to reach the 912Å-1150Å spectral region and for experiments which involve polarimetry. It was concluded that the pallet-mounted configuration would receive the primary attention of the FDT, but that future consideration of the AFPC would not be ruled out until the costs and other disadvantages of interfacing with a Spacelab module could be better defined.

A further study of the AFPC has been carried out at Johnson Space Center. The most notable result to date is the conclusion that the AFPC with a six-man crew can be operated for 30 days with a landed weight margin of 500 pounds available to other payloads. The landing weight of the AFPC exceeds the landing weight of a pallet-mounted SUOT by 4,500 pounds (see Section VI. F). Reasonable methods of attaching the AFPC telescope mount to Spacelab have been worked out, but the costs and management complications of such an interface are difficult to predict at this time. Although there is no way to remove the scientific objections to the tertiary mirror, it is possible, at some expense, to provide a folding mirror, which would thus allow some instruments to operate in the normal cassegrain position directly behind the primary mirror. However, it appears that volume constraints would preclude use of the presently conceived far-ultraviolet spectrograph in such a configuration.

C. Optical Parameters

Concerning telescope optical design, the FDT agreed to the following basic principles:

1. Every effort would be made to maintain a diffraction-limited, flat field diameter of 0°5, in order to take advantage of SUOT's wide-field, high-resolution imaging capability. "Diffraction-limited" is taken to mean image diameters (60% encircled energy) in the 0.2 to 0.3 arcsec range at 4000Å.

2. The 0°5 field diameter will be fully baffled, so that operation on both the day and night sides of the Earth is possible. Full baffling is taken to mean that sky light cannot reach the focal plane sensor either directly or by a single diffuse reflection. Full baffling of the tracking field is also desirable, since no loss in guiding accuracy can be tolerated in the sunlit portion of the orbit.

3. The linear obscuration ratio should not exceed 0.4, so as not to degrade unduly the diffraction-limited image quality. At this level, the percentage of the total light falling within the central peak (with a diameter of 0.2 arcsec at 4000Å) is about 65%.

These principles were primary factors in the decision to adopt a focal ratio of f/15 for SUOT. Although the highest resolution imagery would require a focal ratio of at least 30 if the detector pixel size was not to seriously affect image quality, such a ratio leads to a steeply curved field which cannot be corrected and flattened over a 0°5 field diameter (this assumes that the focal ratio of the primary mirror cannot exceed f/2.5, in order to keep the telescope tube length within reasonable bounds). A large focal ratio also leads to difficulties in achieving full baffling. A reasonable compromise is reached at f/15, where the baffling and field diameter requirements are met while a 0.3 arcsec image diameter corresponds to a linear diameter of 21.8 μm.

Two other factors influence the decision to adopt an f/15 focal ratio: the linear dimension of the 0°5 field and the requirements of the far-ultraviolet spectrograph. At f/15, 0°5 corresponds to 130 mm, whereas at f/30 it corresponds to 260 mm. Since magnetically focused image tubes with 140 mm photocathode diameters currently exist, it seems highly possible that electrographs of this size might also be developed within the next ten years. On the other hand, it is unlikely that any sensor other than unaided photographic emulsion can accommodate a 260 mm field within this time frame. In the far-ultraviolet spectrograph, instrument length is proportional to the focal ratio of its collimator. Thus, there is a considerable length and volume advantage to operating at f/15. Beyond this, preliminary analysis of the far-ultraviolet spectrograph indicates that the f/15 focal ratio optimizes its design in terms of correcting aberrations and matching detector resolution to optical resolution.

D. Instrument Mounting System

The guideline that two or more instruments be mounted for use on SUOT on each mission is highly desirable for at least three reasons: (1) in case one instrument fails, SUOT will not be completely incapacitated; (2) a number of scientific problems make near-simultaneous observations with different instruments highly desirable; and (3) efficient use of orbital time will result when there is carried aboard one class of instrument designed to operate best in the Earth's shadow, and another class of instrument designed to operate best in the daylight portion of the orbit.

Still another dual instrument concept pertains to efficiency: since the direct-imaging survey is one of the primary objectives of SUOT, it is highly desirable that direct-imaging camera exposures be made on every field at which SUOT is pointed and stabilized. Particularly in the case of the spectroscopy of stars, it should be possible to conduct spectroscopy and direct imaging simultaneously by allowing the light from the single star to pass through a hole in a diagonal mirror which diverts the remainder of the field to the direct-imaging camera. This concept, together with the requirement that both the far-ultraviolet spectrograph and the precisely calibrated spectrophotometer should avoid all unnecessary reflections, leads to an instrument configuration in which one of these spectrographs is mounted on axis, while the direct-imaging camera is mounted 90° to the optical axis, on nearly all flights.

At least three other 90° positions are also available. The FDT feels that one of these should be occupied by the very resolution planetary camera which should be carried on nearly all missions and another by a field-viewing vidicon arrangement to be utilized for field identification and general troubleshooting on all missions. The remaining position might be occupied by another spectrograph (dimensional constraints may not permit this), a filter photometer or whatever other instruments might be eventually proposed for SUOT. It must be recognized that if SUOT is mounted on a conventional yoke mount, the instruments at two of these 90° positions can extend no further than 0.5

TABLE 4

SUMMARY OF MECHANICAL AND OPTICAL SPECIFICATIONS FOR SUOT

Maximum length	5m
Maximum diameter	2m
Maximum mass	2000 kg, of which 500 kg are reserved for focal plane instruments.
Clear aperture	At least 1m
Mirror coatings	Nominally, Al + Mg F_2 optimized for the 1150Å to 30,000Å range; optionally, Al + LiF optimized for the 910Å to 1200Å range.
Field diameter	At least 0°.5, nominally; may be smaller when highest resolution (planetary) cameras are used.
Image diameter (60% encircled energy)	0.3 arcsec over a corrected flat field diameter of at least 0°.5 and over a wavelength range from 2500Å to 8500Å (including all sources of image degradation except detector resolution).
Baffling	Both the science field and the tracking field will be fully baffled, so that all stray light requires at least two reflections to reach the focal plane.
Focal plane viewing	The operator should be able to view both the science and the tracking fields during field acquisition.
Guiding system	Will provide at least two sensors and an image motion control system capable of providing image guiding accurate to $\pm$ 0.03 arcsec (1σ) with a 5 Hz bandwidth when sensing stars of $V \leq 13.0$.
Control and data management	Provisions will be made to control the telescope and to monitor the data output from either the Payload Specialist Station or a ground control center.
Thermal control	The primary operating temperature will be 20°C. Control will be sufficient to prevent significant change in focus over an interval of 10 hours. The scientific instrument environment temperature shall be 20°C $\pm$ 10°C.

Table 4 (cont.)

Power	Should not exceed 1 kw average of which 350 watts are reserved for focal plane instrumentation.
Vibrational frequency	The first bending mode of the overall telescope assembly shall be $\gtrsim 30$ Hz.

meter off the optical axis. If the "inside-out gimbal" Instrument Pointing System (IPS) being developed by ESA is used as a mount, then currently proposed constraints indicate that instruments may extend as far as 1 meter from the optical axis.

It is envisioned that either a rotating or a linear array of diagonal mirrors can be used to shunt the light beam of SUOT to the various instruments. Some of these mirrors must be perforated to allow simultaneous use of a spectrograph with the imaging camera. When direct imaging is conducted in this mode, it is necessary to tolerate a field with a central hole 2 cm in diameter surrounded by a vignetted halo with a total diameter of 4 cm. Although the loss of this area may appear undesirable, it should be noted that it constitutes only 9% of the total field area. The size of the mirror perforation is determined by the need to place field correctors approximately 200 mm in front of the focal plane for direct imaging. This distance plus space for the diagonal mirror requires a distance of about 300 mm from the center of the mirror to the focal plane. Thus, the f/15 converging beam of the spectrograph star requires a 2 cm hole in the diagonal mirror.

It is generally conceded (to reduce the dimensions of pick off mirrors and to optimize the quality of focal plane tracking in the direct imaging mode) that the focal plane tracking system should be associated with the beam directed to the direct imaging camera. This presents no particular problem in guiding for other instruments except for the requirement that the diagonals for those instruments incorporate an annular mirror situated so as to divert the rim of the field to the star trackers.

E. Pointing and Stabilization System

For reasons of economy NASA has interpreted Guideline 11 to mean that SUOT should make use of the Spacelab Instrument Pointing System (IPS) as a basic mount for pointing and stability. In principle, this does not seem unreasonable, but since the detailed performance specifications of IPS are not yet clearly defined, there remain large areas of uncertainty in the feasibility of this approach. The IPS performance specifications which are recommended by the NASA Payload Planning Steering Group are listed in Table 5. These specifications, so far as they go, meet the requirements of SUOT well. The stability of $\pm$ 1 arcsec (3σ) along the optical axis requires that the telescope incorporate a secondary stabilization system to achieve the $\pm$ 0.03 arcsec stability which is ultimately required, but this is to be expected. The roll stability of $\pm$ 2 arcsec is adequate to provide full stability control in roll. SUOT could tolerate as much as a $\pm$ 20 arcsec (3σ) stability error in roll, since this translates into a motion of $\pm$ 0.03 arcsec (1σ) in an image lying at the edge of a 900 arcsec field radius.

TABLE 5

INSTRUMENT POINTING SYSTEM (IPS) REQUIREMENTS
REQUESTED BY THE NASA PAYLOAD PLANNING STEERING GROUP

Requirements	Units	1980 through 1983 Stellar	1980 through 1983 Solar	1980 through 1983 Earth	After 1983 Stellar	After 1983 Solar	After 1983 Earth
Physical:							
Payload Capacity (A)							
Diameter	m	2[c]	1.6	2	3.7	2	18[d]
Length	m	6	7	1.5	9.5	7	18[d]
Mass	kg	3000	1200	1000	5000	1300	1500
Payload Capacity (B)							
Diameter	m	0.8	0.8	-	0.8	0.8	-
Length	m	3	4	-	3	4	-
Mass	kg	400	300	-	400	300	-
Gimbal Range							
LOS Angle	deg	±50	±5	±70	±90	±5	±70
Roll Angle	deg	±90	±90	-	±90	±90	±90
Performance: (3σ)[a]							
Pointing Acc.-LOS	arcsec	±1	±1	±180	±1	±1	±5
-Roll	arcsec	±120	±60	±360	±120	±60	±30
Stability -LOS	arcsec	±1	±1	±1	±1	±1	±1
-Roll	arcsec	±2	±10	±2	±2	±10	±2
Gimbal Slew Rate[b]	deg/min	30	5	90	30	5	90
Typ. Stability Duration	arcsec	3600-5400	10-1000	60	3600-5400	10-1000	2700
Interfaces:							
Cryogens	Type	LHe,LN_2	None	None	LHe,LN_2	None	None
Electrical Wires	No.	250-300 plus 10 coax	10-20 plus 10 coax	10-20 plus 1 coax	250-300 plus 10 coax	10-20 plus 10 coax	10-20 plus 1 coax

NOTES:

Earth pointing instruments will require specialized pointing systems. Commonality with stellar & solar pointing IPS uncertain.

a. Pointing and stability to be maintainted within specified boundary with a 3σ (99.7%) probability.
b. Ave. rate for traveling full gimbal range.
c. This value is based on cooling with LHe. The use of supercritical He would increase this value to 2.4m.
d. Deployed antenna.

It is important that the telescope mount provide roll control of at least this accuracy, else a rather expensive image rotating system must be built into the SUOT focal plane instruments.

However, the specifications in Table 5 do not cover important areas of the interface between SUOT and the IPS. Optical studies indicate that the tilt of the secondary mirror to accomplish fine stabilization of the images must not exceed ± 9 arcsec, else appreciable degradation of image quality will result. Thus, it is clear that, whether Shuttle is in a free drift or a limit cycle mode, the IPS must be an integral part of the fine stabilization system. Not only must it be able to accept signals from the SUOT focal plane sensors (a concept currently accepted by IPS designers), but it must also accomplish its compensating motions with accuracies and time constants compatible with the SUOT focal plane guiding system. The current technology for this system envisions a 0.1 sec update cycle. If we accept the 0.1 sec time constant, then the IPS tracking motions must be designed so that unanticipated image displacements greater than 0.03 arcsec cannot occur in an interval shorter than 0.1 sec. Since for a constant acceleration a and a time interval t the image displacement is equal to $1/2\ at^2$, this results in a requirement that stray accelerations not exceed 6 arcsec sec^{-2}. These and more general requirements placed on the IPS by SUOT are listed in Table 6.

It is a basic SUOT requirement to minimize firing of the vernier thrusters. The primary reason is to avoid the contamination generated by these thrusters, but the effects on image motion compensation are also a factor.

If the thrusters must be used, it would be extremely helpful for the Shuttle to provide a gate signal just prior to a thruster firing so that an instrument could be turned off while the environment is temporarily contaminated. The option of stabilization with a control moment gyro kit should also be given further consideration.

The FDT recommends that strong consideration be given to placing Shuttle in a free drift mode during exposures. As long as average drift rates do not exceed 0°.02/sec, there should be no problem in making exposures as long as 50 minutes without thrusting. However, if gravity gradients cause higher rates in this time interval, then the possibility of using either the Shuttle digital autopilot or manual thruster control to provide occasional rate corrections is an acceptable alternative.

It is necessary that the IPS compensate for the Shuttle drift rate during the exposure. Thus the IPS must be able to track anywhere within its gimbal range, ± 60°, at a rate of at least 0°.02/sec while maintaining a pointing accuracy of ± 6 arcsec

TABLE 6

SUOT REQUIREMENTS ON THE IPS
(All values are 1σ)

Control Axis	Stability	Acquisition Error	Setting Accuracy	Max. Rate for Guiding	Maximum Acceleration	Slew Rate	Settling Time
Pitch & Yaw	±2"[a]	±1'	±2"	≥ Shuttle orbital rate (∿4°/min)	±6"/sec² See Note c.	30°/min	One minute to reach ±0".3/sec after initial lock on
Roll	±6"[b]	±1°	±400"				

NOTES:

a. The ultimate SUOT stabilization requirement of ±0".03 will be provided by an image motion compensation system internal to SUOT.
b. Assumes that all roll control will be sensed and controlled by IPS.
c. Allows ±0".03 displacement in 0.1 sec update cycle.

Additional SUOT Requirements:

(1) Maximum time in free drift mode, 30 minutes (requires capability for precise tracking over angles which may be as large as 40°).

(2) Gimbal range, ±60°, with pointing and stabilization accuracies given above.

(3) The jitter rate of the IPS star tracker must be less than 0.3 arsec/sec (1σ).

(3σ) and with accelerations constrained to values less than $\pm$ 6 arcsec sec^{-2}. It is recognized that this requirement may be a rather stringent one ana chat certain tnese constraints (i.e., the maximum slew angle and/or the maximum drift rate) may be traded off against the degree of contamination which is acceptable. Nevertheless, this problem illustrates the intimate relationship between the IPS, SUOT, and potential modes of operating SUOT.

V. ILLUSTRATIVE FOCAL PLANE INSTRUMENTS

It is expected that SUOT will permit the use of a wide variety of focal plane instruments. Most of these will be designed and built under the supervision of scientists interested in particular scientific objectives. However, the relationship between the design of a telescope and its basic instrument complement is so intimate that it is necessary to consider in some detail the design and performance of its basic instrumentation before arriving at a final design for the telescope. It is logical that the instrumentation for the four high priority programs listed in Section II serves this purpose. A brief description of the current concept of each of these instruments, its performance specifications and its technological problems, if any, follow.

A. Direct Imaging Camera (DIC)

The basic performance required of the direct imaging camera (DIC) is that it produce image diameters of 0.3 arcsec or less over a flat field having a diameter of at least 0.5 degrees over as large a wavelength range as possible. We note that, within the proposed optical constraints, fused silica will yield a wavelength range from 2800Å to 8000Å and CaF_2 will yield 2400Å to 8000Å. If direct imaging at shorter wavelengths is desired, it is expected that the refractive elements will be removed and that the consequent loss of field diameter will be accepted. Field curvature will limit this field to a diameter of about 0.1 degrees. It is not foreseen that direct imaging at far-ultraviolet wavelengths will be of primary importance to SUOT.

As currently conceived by the FDT, the DIC includes field correctors, sensors for the focal plane guidance system, a filter system, a field flattener, a detector and interchangeable film magazines. The guidance sensors may either lie behind the field correctors and use them to achieve their required image quality or lie in front of the correctors and employ their own corrector system. The FDT is willing to consider sensors which extend into the data field so long as their width is not much greater than 10 mm. If such a system is used, it is then highly desirable to place the sensors behind the correctors and as close as possible to the focal plane, in order to minimize vignetting in the converging beam. However, in this case, it will be necessary to provide annular field correctors for the guidance system whenever direct imaging without refractive elements is desired. It is doubtful that it would be feasible during the course of a mission to convert from far-ultraviolet image sensing to visible light image sensing, due to the mechanical complexity of such steps as interchanging these elements, removing the field flattener, and refocussing.

This is an operation which might be considered only if an accessible focal plane configuration were adopted, thus allowing these changes to be made manually.

The FDT recommends that the DIC be constructed so that detectors may be easily changed between missions, since it is likely that a variety of detectors may be used for different observational programs. Making such changes via EVA should not be ruled out.

The ideal detector for the DIC has four basic requirements: (1) a sensing surface at least 130 mm in diameter, (2) a pixel diameter on the order of 10 μm, (3) as high as possible a quantum efficiency (hopefully, at least 15%), and (4) a large dynamic range. No one sensor currently exists which meets all these requirements. However, three current sensors meet three out of the four requirements: fine-grained photographic emulsions, certain image tubes, and electrographs. Since each of these three sensors may potentially be improved to also meet the fourth requirement, the FDT is optimistic that, with only a minimal investment in development, an "ideal" detector for SUOT will be available by the 1980's. In the meantime, any one of the above detectors at their present level of development may be considered a suitable detector for particular direct-imaging objectives.

Fine-grained photographic emulsions meet the requirements for field size very well and for pixel size and dynamic range moderately well, but have relatively low quantum efficiencies. Kodak III a-J is probably the most suitable of the currently available emulsions. When properly sensitized and processed, it yields a detective quantum efficiency of about 3%. In its present form, it would be useful for many of the wide-field, survey-type functions listed in Section III A if exposure times of several hours per field were permitted. However, this time requirement plus the lack of any current expectation of an increase in sensitivity renders the bare photographic emulsion the least promising of the three detectors.

At least one currently available image tube, the magnetically focussed ITT 140 mm tube, satisfies the requirements for field size, quantum efficiency and dynamic range (marginally), but not for resolution. Its pixel diameter is about 50 μm, but there is hope that this may be improved by a factor of about two with only a modest development effort. One of the most encouraging aspects of this detector is that it demonstrates the ability of a relatively simple and rugged magnetic focussing system to maintain sharp focus over such a large field. Its resolution is limited by the resolution of the phosphor and the problem of transferring the image from the phosphor to the photographic emulsion, not by the focussing system. It remains to be demonstrated whether the basic quality of the electron image can be held to a 10 μm pixel size, but workers in the field are optimistic that such quality can be achieved. Even in its current form, the ITT 140 mm tube would be an effective detector for programs such as 3d, e, f, g and 4a (see Section IIIA), where high linear resolution is not a prime requirement. It would also be useful in any program where it is permissible to use projection optics to increase the linear size of the optical image at the expense of angular field diameter. One potential problem to be investigated is the effect of the particle radiation environment on detectors, such as the ITT tube, which use phosphor output.

Currently available electrographs satisfy the requirements for pixel size, quantum efficiency and dynamic range, but so far none have been operated with photocathode diameters in excess of 50 mm. However, in view of the demonstrated capability of the ITT image tube mentioned above, workers in the field are optimistic that such a large format electrograph giving pixel diameters of 10 μm is feasible. Such an instrument would be ideal for SUOT as well as for many other astronomical applications, and the FDT recommends that NASA give all possible support to the development of such a detector.

It must be acknowledged that the complexity of operation of current ground-based electrographs is a factor which discourages their use. This complexity arises from the fact that the bi-alkali and tri-alkali photocathodes used for visible and near infrared wavelengths are extremely sensitive to chemical deterioration when exposed to even minute amounts of water vapor. Thus, they must be protected not only from exposure to the atmosphere but also from the water outgassed by the recording emulsions. Either extensive pump-down and outgassing of the emulsion is required before it is exposed to the photocathode, or else a very thin membrane capable of transmitting high-energy electrons but not water molecules must be interposed between the emulsion and the photocathode. However, space telescopes have two special advantages which mitigate these problems. First, the photocathodes sensitive in the region from 1100Å to 3000Å (KBr, CsI, and CsTe) are relatively unaffected by water vapor and may be operated without the complex protective procedures. Secondly, when the bi-alkali and tri-alkali photocathodes must be used, space operation provides a vacuum environment in which outgassing of large amounts of emulsion can be effected with a minimum of effort. This is not to imply that these photocathodes can be exposed to the ambient atmosphere of the Shuttle environment. Even this will be detrimental to these surfaces and further pump down of the emulsion is necessary. However, such pumping effort should be minimized by the preliminary outgassing to the space vacuum. A further factor in improving the utility of electrographs both on the ground and in space are recent improvements in thin protective membranes, which may be used to protect the photocathode from the emulsion and thus eliminate any need for outgassing or further pump down of the emulsion.

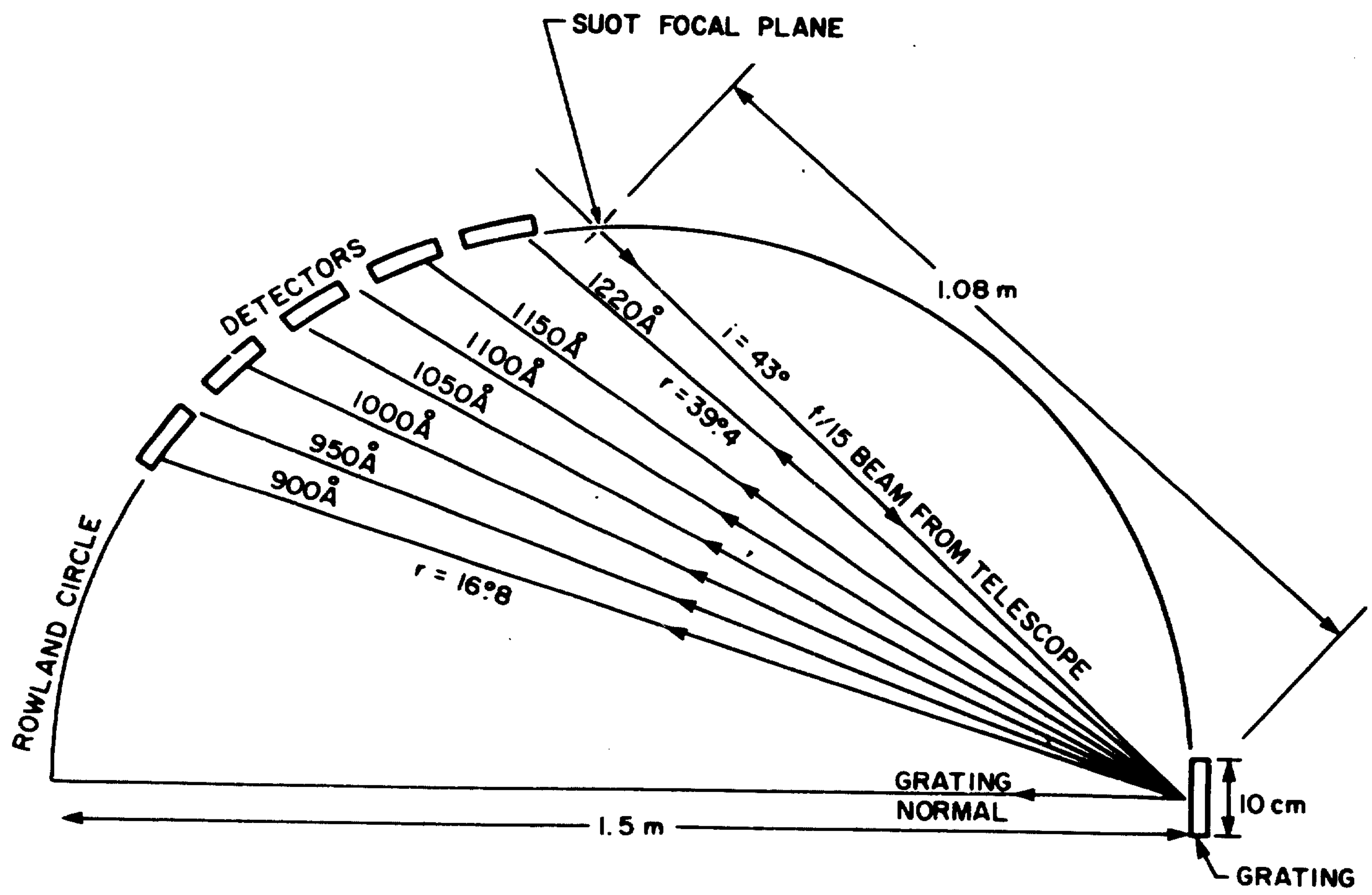
Two other factors which make electrographs highly desirable detectors should be noted here. The first is the availability of several different photocathode materials which are sensitive to various regions of the UV spectrum but not to visible light. Thus, these photocathodes provide long wavelength sensitivity cutoffs in the UV which cannot be efficiently accomplished by any available transmission filter. This is still an unsurmounted handicap when one contemplates isolating broad bands in the UV with bare photographic emulsion as the detector. The second factor is the very wide dynamic range and the linear response of the nuclear track emulsions used to record the electron images in electrographs. Thus the information storage capacity is much greater than that of ordinary photographic emulsion and the calibration and interpretation of the density versus intensity relation of the emulsion is much easier.

One aspect of both the image tube and the electrograph which bears careful consideration when configuring the focal plane instruments is the volume required by their focussing systems. For example, the ITT 140 mm image tube has a basic magnet diameter of about 300 mm and this is increased to about 500 mm if magnetic shielding is required.

B. Far-Ultraviolet Spectrograph (FUS)

The current concept of the FUS is described in Section b of Appendix C, and is illustrated in Figure 4. A Rowland configuration is dictated by the need to minimize the number of reflections in the instrument, since each reflection causes a light loss of at least 50% in this wavelength region. This requirement also necessitates aligning the FUS optical axis with the optical axis of SUOT in order to avoid the use of a diagonal mirror. The length of the FUS also dictates this configuration. Optical design studies of SUOT have demonstrated the feasibility of placing the FUS detectors forward of the f/15 focal plane, as implied in Figure 4.

It is highly desirable that the resolution of the FUS exceed that ($2X10^4$) of the *Copernicus* spectrometer by a significant factor, since the *Copernicus* data is found to have a velocity resolution which is marginal for some interesting astrophysical problems. As Appendix C indicates, the resolution of the FUS will probably be limited by detector resolution. The $4X10^4$ resolution of Appendix C is based on a conservative value of detector resolution (50 μm), and it would be surprising if this might not be improved by a factor of two or three by the time this instrument reaches final design.



Figu.'e 4. Schematic Layout of Far-UV Rowland Spectrograph

It is also highly desirable to record large sections of the spectrum simultaneously in order to reach fainter stars than can be reached by the Copernicus scanning spectrometer system. This seems entirely feasible and, as Appendix C (Section c) indicates, the current concept is to use multiple image intensifiers such as microchannel plates with proximity focussing of electrons onto charge coupled devices. Technology is currently advancing rapidly in these areas, and it does not seem overly optimistic that highly efficient linear array detectors suitable for spectroscopy will be available by the 1980's. Indeed, it would probably be unwise to design a telescope around a more conservative concept at this time.

C. Precisely Calibrated Spectrophotometer (PCS)

The heart of the proposed instrument would be a spectrometer, which is shown schematically in Figure 5. As shown, it is a Monk-Gillieson monochromator optimized for third-order aberrations according to the scheme described by Schroeder. It consists of a single concave mirror and a plane grating. A plane grating in a converging beam, as shown, results in coma, and, since coma depends upon an odd power of the off-axis angle, the coma of the mirror can be used to compensate for the aberration which results from differing angles of incidence in different parts of the beam. Astigmatism is also negated in this scheme, and there is no difficulty in maintaining a 10Å spectral purity over the useful blaze of most gratings. In order that optimum grating-blaze/detector combinations be available over the widest possible range of wavelengths, it will be assumed that gratings and detectors can be mounted on turrets or carousels for quick interchange. Gratings should also be rotatable in order to change effective wavelengths. The optical system should have a sufficiently unvignetted field of view to allow for dual-channel operation, which in the simple spectrometer mode of operation would be used for simultaneous sky/background measurement. The entrance apertures would be in pairs, one for object and one for sky. In this connection, an interesting possibility for further study would be the feasibility of accomplishing the switching of the roles of the object and sky apertures, as is standard practice in ground-based systems (e.g., the Lick-Wampler scanner), by means of articulating the telescope secondary in the manner of infrared observers. If this could be done at frequencies of 1 sec^{-1} or faster, with simultaneous switching of counter registers allocated to sky and to background and electronic switching of the guider system, then compensation for rapidly variable, particle-induced background could be accomplished with an attendant increase in the capability of the system for the observation of faint sources. In addition to the entrance aperture plate, the focal plane region could usefully include television cameras (intensified) for target acquisition, centering, and off-set finding/guiding.

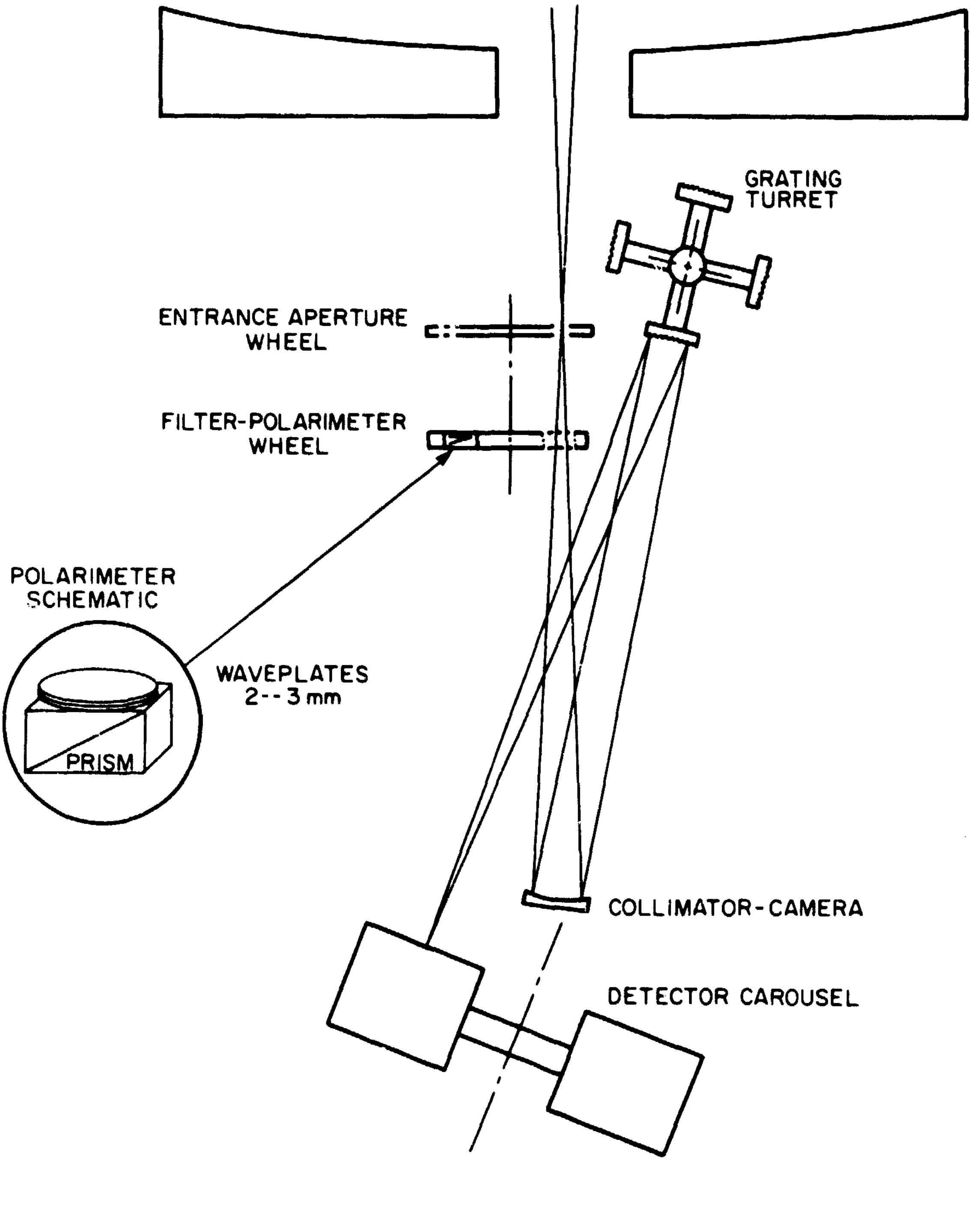


Figure 5. Schematic Layout of the Precisely Calibrated Spectrophotometer

A short distance downstream from the entrance aperture is located a filter wheel, which, in addition to containing order-separation filters, can contain all that is needed to turn the instrument into a spectropolarimeter. The scheme of Nordsieck consists simply of two retardation plates of different thicknesses with their optic axes at a 45° angle to each other followed by an analyzer. The analyzer would be a beam-splitting prism enabling both senses of polarization to be measured simultaneously by the double detector array. The retardation plates modulate, as a function of wavelength, the polarized component of the radiation. From this modulation the four Stokes parameters, I, Q, U, and V, may be determined as follows: If A and B are the spectral intensities observed simultaneously in the two sets of detectors, corrected for instrumental response, then:

$$I\ (\lambda) = A + B$$

and

$$p\ (\lambda) = \frac{A - B}{A + B} = q(\lambda)\ \cos t_2 + u(\lambda)\ \sin t_2\ \sin t_1 - v(\lambda)\ \sin t_2 \cos t_1$$

where q, u, v = (Q, U, or V)/I and $t_i = 2\pi\ (\Delta n) d_i/\lambda$, Δn is the birefringence of the retardation plates, and d_i their thicknesses. The Stokes parameters can be extracted from the data on line by simple Fourier routines.

The detector which would be adequate for this system is a roughly 100 by 2 array of channeltrons, each with its own pulse amplifier-discriminator and counter register. Smaller arrays of these devices have been built, both with and without windows, and have been space qualified, so there is no essential reason that the detector requirements of this system cannot be met. Furthermore, there is the distinct possibility that there will soon be available even more advantageous devices, such as a microchannel plate (MCP) intensified, buffered read-out, charge coupled device or an MCP $\approx$ 500 X 2 element digicon. In order to handle the data generated by such a system, we would expect to require the dedicated services of a nova class computer with some high-density storage such as a disk. With appropriately designed hardware controllers and an adequately flexible software system such as FORTH, it would be possible for one block of data to be reduced while the next is being collected, and thus for fully reduced data to be available as the mission proceeds.

D. Planetary Camera

A detailed concept for the planetary camera remains to be developed. However, the planetary camera is expected to consist of:

1. all-reflecting transfer optics
2. interchangeable spectral and polarizing filters
3. a shutter
4. a detector (with a quantum efficiency on the order of 15%)
5. an internal photometric calibration source.

The transfer optics would correct for any zonal residual aberrations in the main optical system, and would increase the effective focal ratio of SUOT to ensure that the overall system is diffraction limited and not detector limited. Detectors under consideration are silicon vidicons and charge coupled devices with or without intensifiers. Such detectors would require an effective focal ratio of approximately f/60 or f/75.

VI. OPERATIONAL CONCEPTS

A. Makeup and Functions of Shuttle Payload Crew

The FDT recommends as a fundamental principle that the payload crew be of sufficient number and have the proper skills (both technical and scientific) to operate SUOT autonomously if the need should arise. This is not meant to imply that autonomous operation will be the rule. To the extent permitted by the adequacy of orbit-to-ground communcations and telemetry systems, it is expected that the operation of SUOT and its instruments will be a co-operative effort involving a ground team of scientists and technicians as well as the payload crew.

A major factor in how responsibilities for telescope control will be shared by the payload crew and the ground team is the adequacy of orbit-to-ground communications and telemetry systems. The FDT's desire to provide primary control of SUOT by the orbiter crew is based mainly on the current prediction that, at best (with two onboard communication antennas), there will be direct contact between Shuttle and the Payload Operations Control Room (POCR) for not more than 80% of the time and that, when priority conflicts between experiments, between experiments and Shuttle and between Shuttle and other satellites are accounted for, the POCR will probably have direct contact with any one experiment less than 50% of the time. Of course, as the adequacy of orbit-to-ground communcations improves, it would be possible for the POCR to assume more direct control of SUOT if this seems desirable.

Another factor in this recommendation is the consideration that onboard personnel who are completely aware of all aspects of the Shuttle environment (such as changes from night to day, unusual crew motions or thruster operations, and water dumps) and who have continuous and undelayed access to the incoming data will be better able to promptly detect and react to unusual aspects of instrument performance or of the scientific data. They will have an <u>uninterrupted</u> capability for real-time target acquisition and verification, especially important in complex fields. Onboard payload personnel will be in the most advantageous position to implement commands and procedures which require close coordination between payload operations and orbiter operations, for example the simultaneous slewing of IPS and re-orientation of the orbiter (see Section VI.F.2), and the observation of planets at small elongation angles from the Sun. For this reason, we recommend that primary control of IPS and SUOT reside with the onboard payload crew, supported by backup control from the ground.

The onboard crew will be well able to respond quickly to major malfunctions and caution/warning indications. They should also monitor payload function and data reception and be capable of routinely initiating and terminating command sequences and of modifying observational parameters. On the other hand, it is expected that the ground team will be better equipped to evaluate the finer nuances of instrument performance or of scientific significance, but that this will require extended periods of time and can be expected to influence the day-by-day planning aspects of the mission rather than the minute-by-minute control of the telescope and instruments.

An important aspect of this interrelationship between the onboard crew and the ground team is the computerized telescope control system described in Section VI C. With such a system, command may be exercised either from the Payload Specialist Station (PSS) or from the POCR, as circumstances require. Even though operation from the ground may not be as efficient or as flexible as operation from the PSS, it is anticipated that ground operation will be possible through transmission of stored command sequences. Thus, incapacitation of one or more payload crewmen would not jeopardize the operation of SUOT.

The basic four-person Shuttle crew includes two payload-oriented crewmen: the Mission Specialist and the Payload Specialist. It is possible that these two, with assistance from the two pilots, could operate SUOT with reasonable efficiency for a basic seven-day mission encompassing two twelve-hour shifts. However, it is evident that SUOT operating efficiency could be significantly increased by having two operators during each shift (see Appendix E for an illustrative example of how operational tasks might be shared). Further, it becomes highly desirable on missions longer than seven days to provide for occasional days of rest for the crewmen. Thus, even for short missions, and especially for missions exceeding seven days, it appears sensible to fly four payload crewmen. The desirability of a four-person crew becomes even more evident when it is considered that the total payload will probably include several instruments other than SUOT, which may require significant attention from the crew.

Many alternatives exist as to what types of skills are required of the payload crewmen and what their relative functions should be. Probably the most obvious makeup of a four-person payload crew would include two Mission Specialists and two Payload Specialists. It is assumed that the SUOT Mission Specialists will be NASA scientist-astronauts and will be astronomers who are intimately acquainted with SUOT and its operation. Their main function will be to operate SUOT and the IPS, to monitor SUOT and IPS performance, to remedy malfunctions and maladjustments of SUOT and IPS and to operate other instruments in the payload complement. It is to be expected that on early flights, the Payload Specialists will be scientists from the institutions providing the focal-plane instruments. They will specialize in the operation of the focal plane instruments, in monitoring the performance of these instruments, in monitoring the scientific data produced by them and in correcting instrument maladjustments or malfunctions.

The same Mission Specialists will hopefully fly repeatedly with SUOT and, in the beginning, this should also be true of several of the Payload Specialists, since their accumulative experience in instrument operation and in adjusting to the zero-G environment will undoubtedly be an asset. However, after instrument reliability and operating procedures are thoroughly established, it is expected that Payload Specialists with differing scientific interests may fly if they so desire. As new instruments are included in the focal plane complement, new Payload Specialists will fly with them.

Probably the most attractive alternative for the makeup of the payload crew would be to include one Mission Specialist and three Payload Specialists. This arrangement has the advantage of providing a Payload Specialist for each of three focal plane instruments. It should be possible for one or more Payload Specialists to become reasonably proficient in the operation of SUOT and to take over this function during the Mission Specialist's rest period. However, the Mission Specialist should be available around the clock to take charge if significant malfunctions of the SUOT systems should occur. The Payload Specialists should also have enough cross-training to operate each other's instruments, but in the event of a malfunction, the specialist for that instrument should be expected to take charge of the situation.

The work cycle for a four-person payload crew would most logically be organized into two twelve-hour work shifts. The illustrative PSS shown in Section VI C gives adequate room for two operators. It is assumed that full control of both SUOT and its instruments may be exercised at either keyboard, but that more efficient operation may be achieved by having one operator controlling and monitoring the functions of SUOT (and possibly other experiments as well) at one keyboard, while a second operator controls and monitors the functions of one or more focal plane instruments at the second keyboard. Such a system gives the flexibility required to give each crewman a rest day each week during which one-person operation would be accepted.

The weight penalties required to support two extra crewmen for a 30-day mission amount to 650 pounds per person, and are thus not a major factor in the payload weights (see Section VI F). These values include the estimated weight of the person (170 pounds), the weight of his seat, rescue equipment, clothing, etc. (152 pounds) and a time dependent factor of 10.5 pounds/day, which includes food, LiOH canisters (for CO_2 removal), toilet articles, and extra stowage cabinets. More than sufficient water and O_2 are available from the electrical power system kits.

It has been assumed that waste water will be dumped at regular intervals. If waste water is to be stored and returned, then approximately 15 pounds/man-day in excess of a 42 man-day basic allowance must be added to the weight requirement. This requires an additional 450 pounds of weight penalty per additional crew member for a 30-day mission. However, if the water may be dumped at the end of the mission, then the only weight penalty is for tanks which amount to 140 pounds per person for a 30-day mission.

B. Extra-Vehicular Activity (EVA) Requirements

Due to the length of time required for Extra-Vehicular Activity (EVA), it is recommended that SUOT be designed so that EVA will not be required for short (7-day) missions. However, as mission length increases up to 30 days it becomes highly desirable to provide for an EVA capability. One reason will be for the exchange of film magazines on those instruments which employ photographic detectors. However, the primary reason is to provide for possible repair of malfunctioning equipment.

Skylab experience indicated that one of the more frequently required functions of man in orbit is to troubleshoot and remedy instrument malfunctions. Therefore, it is recommended that critical functions (particularly those in the telescope facility, such as removal of the telescope end cover, and motion of the diagonal mirror) be designed for EVA accessibility. It is particularly recommended that in case of failure of the pointing system that manual means to return to a reentry stowage configuration be made possible via EVA, in order to avoid possible jettisoning of the telescope.

C. Telescope Control and Data Management

A number of basic concepts enter into formulation of the system for controlling the telescope and managing the data (both systems and scientific) which flow from it. Among these are:

1. The telescope must be controllable from both the PSS and the POCR.

2. The control and display system must allow control of SUOT (and the IPS), control of the focal plane instruments, display of systems status and scientific data from the instruments, and at least limited analysis of scientific data.

3. Simultaneous activity by a least two operators onboard the orbiter is highly desirable.

4. The SUOT control and display system should not be so dedicated or so extensive as to prevent operation of other experiments as well.

5. The control and display system should be able to accept instrument modifications or new instruments without requiring major alterations.

6. The system should be flexible and easy to operate.

The requirements for flexibility and compactness in the control and display system lead logically to the concept of computer-controlled telescope and instruments, with primary control and display being exercised through a computer terminal equipped with an alphanumeric keyboard and a video display device. (Although cathode ray tubes (CRT's) are now generally used for video displays, rapid advances in low-power video display devices other than CRT's may be highly desirable on the Shuttle.) Such a system lends itself equally well to entries from the PSS or from the POCR via up-linked commands and down-linked data flow. Modification to the telescope or addition of new instruments will have essentially no impact on the control and display system. Indeed, the concept of a computer-controlled system makes possible the design of a universal PSS which is suitable for all payloads willing and able to accept computerized control of their instruments. And, finally, there is the advantage that several large ground-based telescopes are now being controlled in a similar manner so that most astronomical observers and instrument designers are becoming familiar with the concept. These ground-based systems employ an easy-to-learn, user-oriented computer language called FORTH. It is expected that the SUOT would use a similar language.

A preliminary concept of a two-panel PSS is shown in Figure 6. Each panel has a basic keyboard and CRT for access to the payload computer. A second CRT is also available for video-type displays such as star fields and slit-jaw viewing. Each panel also contains a time display, including count-down timers, a number of dedicated switches for those functions where back-up, hard-wire control is desired (such as stow commands and jettison commands), and a number of lights to indicate status and malfunction warning. It is expected that the left operator would be primarily responsible for operation of the main telescope and that the special lights and switches on the left panel would be related to the telescope. The right operator would be primarily responsible for operation and monitoring of the focal plane instruments, and the dedicated switches and lights on that panel would be connected mostly with those instruments.

One function, in particular, which is not conveniently performed by digital inputs is the fine adjustment of telescope pointing. Therefore, the lower right section of the left panel contains

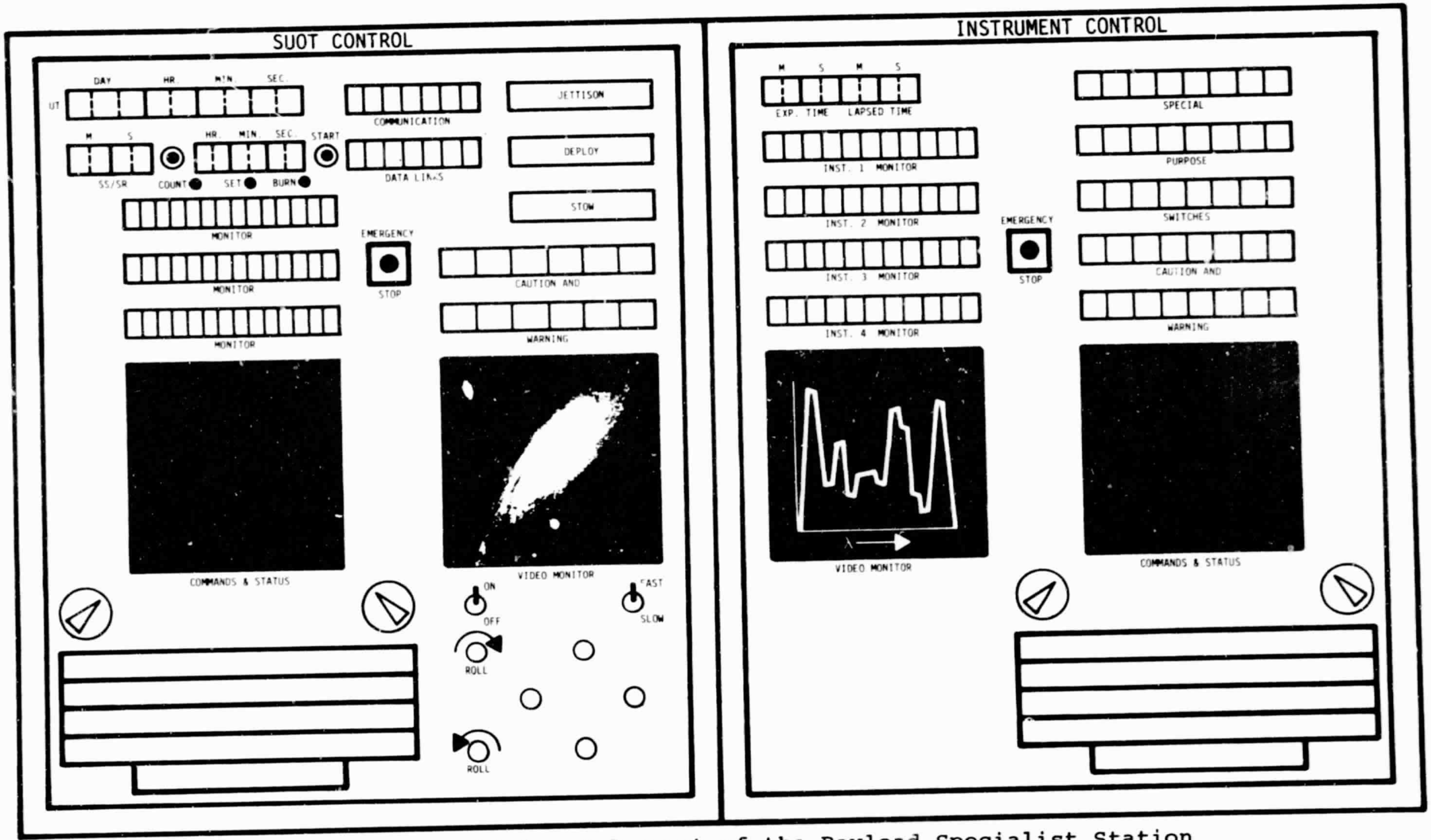


Figure 6. Preliminary Concept of the Payload Specialist Station Required by the SUOT Facility

a manual control system to correct telescope pointing. In this position it may be conveniently used by either operator. It is recommended that the manual control system be a hard-wired system, thus providing complete redundancy to a digital control system operated through the computer.

It is to be emphasized that this panel configuration is compact enough to be operated by one person, even though some efficiency may be lost in one-person operation. Either keyboard could be used to control both telescope and instruments as well as any other computer-controlled facilities which may be onboard. If some of the other facilities onboard require a dedicated control panel, this may be located on the third PSS panel not shown here or at the payload-dedicated panel at the Mission Specialist Station (MSS). However, it is to be hoped that all onboard facilities would accept the computer controlled concept. In this case, the third PSS panel would be used for whatever dedicated switches and status lights are required by these facilities and the MSS panel would be a duplicate of the Instrument Control panel, thus enabling a third operator to control and monitor certain of the focal plane instruments and/or the other facilities which may be onboard or else to examine previously acquired data.

Data examination onboard and the fact that the Tracking and Data Relay Satellite (TDRS) will not always be available for immediate data down-link give an urgent requirement for a temporary, random-access storage device onboard Shuttle. Such onboard data examination is an essential element in maintaining the high observing efficiency promised by the presence of onboard scientists. Although such storage devices are not now a part of the Shuttle data management system, it is recommended that every effort be made to develop a space qualified random-access storage system which may be incorporated as a part of the payload electronic package.

A detailed consideration of up-link and down-link data rates is given in the Ball Brothers Research Corporation (BBRC) final report (October 1975). The FDT confirms that the stated requirements are adequate and, specifically, that the down-link data rates are probably greater than will be required. However, it must be emphasized that the bit rate between the Spacelab pallet and the PSS is very marginal and serious consideration should be given to increasing it to at least 10^6 bits/sec (see Section VI.F.4). An illustrative example of the sequence of functions controlled at the PSS when the Direct Imaging Camera and the Precisely Calibrated Spectrometer are simultaneously opera d is given in Appendix E.

D. Payload Operations Control Room (POCR)

With the exception of a few "hard-wired" controls directly linking the Payload Specialist Station with SUOT (see Section VI.C), control of IPS, SUOT and its focal plane instruments will be implemented through an interactive computer system, using the Spacelab payload computer and supplementary processors, as required. This fact, coupled with the similarity between the controls and displays envisioned for the PSS (see Figure 6) and those commonly used in ground-based satellite control centers, will greatly simplify the development of a complementary SUOT control capability in a ground-based control room, in parallel to that at the PSS. The relative balance of responsibility between Payload Specialists and the ground team for the routine operation of SUOT will ultimately depend on the availability of nearly full-time TDRS coverage on the one hand (a capability about which the FDT has serious misgivings at this time) and the total workload of the Payload Specialists on the other. As we have emphasized in Section VI.A, there are control functions which are clearly most advantageously performed by the payload crew in orbit and which should be reserved to them, backed up by emergency control from the ground where feasible. Similarly, ground-based operations will provide essential support capabilities which most logically reside in the POCR facility.

Throughout the mission it is expected that technical and scientific representatives of the institutions responsible for SUOT and for each of its focal plane instruments will form a ground team to man the POCR. The primary function of this team would be to monitor in detail the technical quality and the scientific importance of the data being telemetered to the ground. On the basis of such monitoring, the ground team would then undertake such activities as formulating or modifying the long range observing programs, and formulating malfunction procedures to correct subtle causes for loss of data quality not obvious to the onboard crew. This function requires that all data telemetered by the Orbiter be immediately transmitted to the POCR and that the POCR have facilities for analysis and quick display of the incoming data.

It is expected that the nucleus of the SUOT control system will be a library of command sequences governing IPS maneuvers, SUOT subsystems control and focal plane instrument operations. This library could either be stored in an accessible memory onboard Shuttle prior to launch or it could be telemetered in segments from the ground as the flight proceeds. Such command sequences might be organized into subroutines covering all or major parts of the observing run on the sequence of targets planned prior to launch. This software would be flexible in that, for example, various parameters related to IPS, SUOT and instrument control could be varied as input data, the times of initiation and termination of sequences could be controlled, and command sequence subroutines could be edited. These command programs could be implemented and the parameters could be varied either at the PSS or in the POCR. However, the major editing or modification of command sequence programs or the generation of new programs with the attendant debugging should be left in the hands of the ground-based payload team.

If the necessity arises, preloaded command sequences might operate the telescope without supervision by the orbital crew or the ground team (during TDRS outages, for example), but it is probable that such operation will be restricted to fields in which, for example, the target object and guide stars are all bright and free of confusion by nearby stars.

Other functions of the ground team would include providing finding charts and information on guide star locations for fields not included in the original flight plan, and keeping the flight crew updated on observing program status and the scientific insights gleaned from inspection of the telemetered data.

E. Orbital Constraints

The most important orbital constraint will be to achieve orbits in which the Sun will lie near the orbital plane for as long a period as possible throughout the mission in order to maximize the length of orbital night, since a number of instruments (the direct imaging camera in particular) will be significantly affected by the brighter sky background during the sunlit portion of the orbit. For 1-week missions there should be little difficulty in meeting this constraint, but for 30-day missions it will be impossible to satisfy completely due to orbital precession.

The optimum orbital altitudes lie between 200 and 400 nautical miles -- high enough to avoid significant aerodynamic drag interference with Orbiter attitude, but not so high that van Allen belt particles will significantly affect electronic detectors. At these altitudes the orbital period will be roughly 95 minutes, of which 40 minutes will be in Earth's shadow if the Sun lies in the orbital plane. The depression of the horizon will be about 15° and objects in the orbit plane will be more than 5° above the horizon for about 50 minutes of each orbit. Objects lying out of the orbit plane will be visible for a larger fraction of the orbit. Thus, for objects which can be observed only in the Earth's shadow, the maximum interval of observation will be 40 minutes and for objects which may be observed in the shadow or out the interval ranges from 50 minutes in the orbit plane to unlimited for objects within 10° of the orbit poles.

F. SUOT - Orbiter Interfaces

The interfaces of interest include (a) stabilization, (b) attitude control and maneuvering, (c) contamination, (d) utilities and (e) payload weight restrictions.

1. Stabilization

It is to be expected that SUOT will generally require Shuttle to be stabilized in a wide dead-band mode or to be in a free drift mode during observations. It is desirable to minimize firing of all thrusters during observations, in order to minimize contamination and to eliminate the guiding excursions which may result from such angular accelerations.

Whether a wide dead-banding mode or a free drift mode is better depends mainly on the magnitude of the gravity gradient accelerations acting on Shuttle. If the average drift rate over a 50-minute exposure can be maintained at 0.02 deg/sec or less, then the total drift will be 60°, a value compatible with an IPS operational cone-angle of $\pm$ 60°. The question remains as to whether the Orbiter can maintain such low rates in an inertial orientation. The most favorable orientation appears to be with the long axis of the Orbiter perpendicular to the orbital plane (the X-POP mode). In this mode the Orbiter is in an unstable equilibrium. Although gravity torques may initially be zero, any slight deviation in attitude will produce a small torque which will increase with time. Also, gravity torques about the roll axis are zero only when the wing plane is perpendicular to or parallel to the direction to the nadir, a condition which can be met only momentarily when the Orbiter is inertially stabilized. At other positions, a torque will exist, but its direction will be reversed every quarter of a revolution. Although studies of orbiter stability under these conditions are only fragmentary, preliminary data indicate that rates may build up to 0°.05 /sec in the course of 5 to 10 minutes and, therefore, that thruster firings every 5 to 10 minutes may be required to keep both tracking rates and IPS slew angles within acceptable tolerances. However, such infrequent thruster use should be tolerable, and it is anticipated that the thrusters may be controlled either manually or by setting appropriate rate and/or pointing error limits in the Digital Autopilot (DAP) of the spacecraft control system. The manual mode has the special advantage of allowing telescope covers to be closed before thruster firing begins if contamination is a serious problem. Also, it is likely that carefully planned manual thrusting would result in less total thrusting (and, therefore, less contamination and propellant use) than would DAP control.

2. Maneuvering Requirements

It is a basic requirement that at least two objects be observed each orbit, in order to avoid wasting observing time during the interval any one object would be occulted by the Earth. If no use were made of the IPS pointing capability, then two 180° maneuvers would be required each orbit. If each maneuver were made at 1/2°/sec in roll only, then 6 minutes and 7 pounds of propellant would be required for each maneuver. This is objectionable mainly because a propellant usage of 17 pounds per orbit or 7,650 pounds per 30-day mission (assuming 3 pounds per orbit for attitude control plus two roll maneuvers per orbit) significantly exceeds the basic 4,000 pounds per mission allowance for RCS propellant. The potential contamination effects of this propellant are also a matter of concern, and it is clear that every effort should be made to reduce RCS propellant usage.

Such a reduction can be achieved by substituting SUOT slew capability for a large fraction of the total maneuvering angle. Figure 7 illustrates basic roll and slew requirements for viewing two or three objects per orbit. It is assumed that the Orbiter is oriented in the X-POP mode so that all maneuvers are roll-only maneuvers, the roll axis being the most economical axis for rotational maneuvers. It is also assumed that the IPS is fully operational over only a $\pm$ 60° cone angle.

A further simplification of Figure 7 is that only targets lying in the orbit plane are considered. When out-of-plane objects are viewed, the possible viewing interval for each attitude is increased (assuming that night and day considerations are not a problem), and the sky area in which objects may be chosen becomes somewhat more flexible than is indicated in the figure.

The basic conclusion to be drawn from Figure 7 is that, regardless of the number of objects observed, a total of 120° of orbiter roll and 240° of IPS slew will be required during each orbit. If orbiter maneuvers are made at 0°.25 /sec and the IPS can be slewed 30°/min, then on each orbit 8 minutes will be required for orbiter roll and 8 minutes for IPS slew. There is no presently known reason preventing these actions from occurring simultaneously, and such simultaneous operation is obviously highly desirable. Any requirement that IPS gimbals must remain locked (or that IPS be in the stow position) during an orbiter maneuver would greatly increase the time required to repoint the telescope and should be considered an unacceptable restraint.

In Figure 7A, we have allowed 8 minutes from the end of one exposure to the beginning of the next. The repointing process

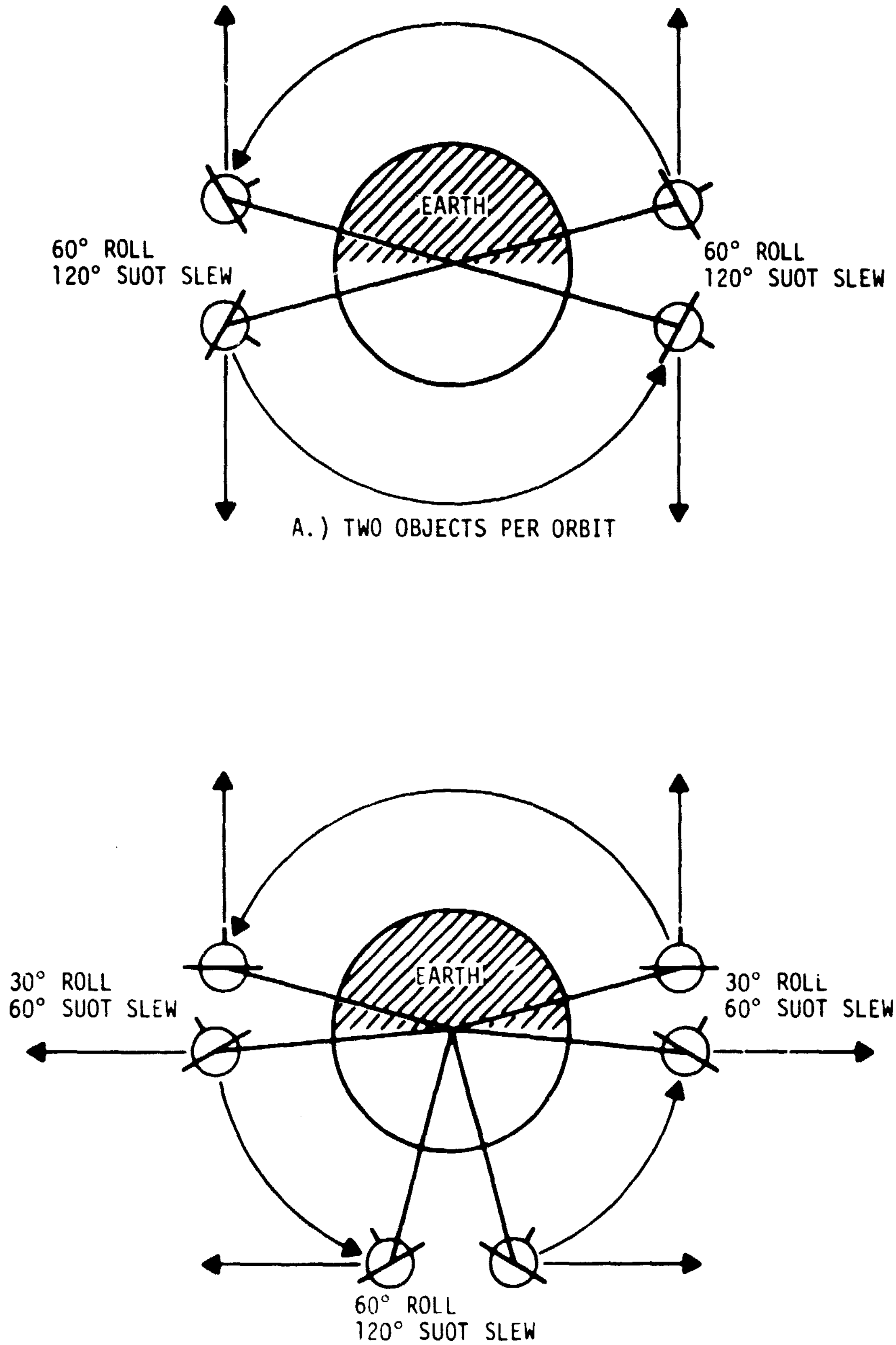


Figure 7. Basic Orbiter Roll and IPS Slew Requirements for Viewing Two or Three Objects per Orbit

requires 5 minutes, and we allow an additional 3 minutes for settling, final pointing and exposure initiation. Total propellant use is 13 pounds per orbit (assuming a maneuvering rate of 1/4°/sec in roll only and 3 pounds per orbit for attitude holding), or 5,850 pounds per 30-day mission.

In Figure 7B, we have allowed 6 minutes for each of the two short maneuvers and 8 minutes for the one long maneuver. The actual repointing times are 3 and 5 minutes, respectively, and 3 minutes are allowed in each case for settling, fine pointing and exposure initiation. Total propellant use is increased to 18 pounds per orbit or 8,100 pounds per 30-day mission. This exceeds the basic RCS allowance, and it is clear that an observing pattern of this sort would be acceptable for only a small fraction of the time.

An extension of the minimum maneuvering logic illustrated in Figure 7 yields a useful quantitative relationship between the operating cone-angle of IPS and the amount of maneuvering required for the Orbiter. It can be demonstrated that, with an IPS cone-angle of ± 90°, no Shuttle maneuvering is required and that, with an IPS cone-angle of ± 45°, the Shuttle maneuver angle must equal the IPS slew angle. It is obvious that Orbiter maneuvering can be minimized by constructing an IPS with a ± 90° cone-angle. However, minimum repointing time is achieved by equating Orbiter maneuvering time to IPS slew time (assuming that both take place simultaneously). If an Orbiter rate of 0°.5 /sec is permissible (a doubtful assumption due to propellant usage on long missions), then an IPS operating cone-angle of ± 45° is adequate. In this case a 180° repoint would require a slew time of 3 minutes. If an Orbiter rate of 0°.25 /sec is used, then an IPS cone-angle of ± 60° is required. In this case a 180° repoint would require a slew time of 4 minutes. If the entire 180° maneuver is performed by IPS, then a slew time of 6 minutes is required. All the above reasoning assumes an IPS slew rate of 30°/min.

Contamination effects are difficult to evaluate. One conclusion which may be drawn from the above illustrative numbers is that nominal attitude hold fuel (3 pounds per orbit, assuming X-POP orientation, altitude of 200 nautical miles or more and ± 0°.1 dead band) is small compared to the fuel required for maneuvering. Thus, if the contamination caused by maneuvering is acceptable, then there should be little problem in using the vernier RCS system to hold attitude within 0°.1 or wider limits, and the constraints on use of vernier thrusters assumed in the previous section may be relaxed. However, the conclusion there that the X-POP orientation is the most desirable for nominal operation is reinforced by the above discussion. X-POP orientation both reduces the fuel required for attitude holding and also keeps the majority of the maneuvering about the roll axis, thus substantially reducing RCS propellant consumption for maneuvering, as well. Rotation about the other two axes requires approximately 1.6 times as much propellant.

It must be noted that some deviation from X-POP mode must be allowed in order to reach targets near the orbital poles, since the ± 60° IPS cone-angle gives access only to objects within 60° of the orbit plane in the X-POP mode. Such deviations are possible, the main disadvantage being that gravity gradient forces will rapidly accelerate Orbiter pitch and yaw rates so that operation of vernier thrusters will be required every 1 or 2 minutes to null the rates if inertial pointing is to be maintained. However, if several objects could be observed sequentially in one of the polar caps, then no Orbiter maneuvers would be required in repointing from object to object, and the total RCS fuel used per orbit would be reduced to a value of about 5 pounds, the amount required for attitude holding.

The above considerations have ignored the most stable attitude of the Shuttle -- the X-LOCAL VERTICAL mode, in which the longitudinal axis of the Orbiter remains roughly aligned with the radius vector to the Earth's center. This attitude mode would seem to be the most desirable mode for free-drift operation <u>if</u> the IPS were capable of maintaining its full stability accuracy while tracking at the orbital rate of 4°/min (0°.067 /sec). However, it seems very probable that such large tracking rates will have a significant effect on stability accuracy. A second problem also remains -- the awkward orientation of the Z-axis, which will always be pointed near the Earth's horizon. If the Z-axis is oriented perpendicular to the orbit plane, objects within 30° of the plane (nearly half the sky) cannot be reached by the IPS. This can be remedied by rotating Orbiter so that the Z-axis lies in the orbit plane. However, in this instance the IPS tracking range will be limited to 70° (from -10° at 5° above the Earth's horizon to +60° at the limit of the IPS cone-angle) and, at an orbital rate of 4°/min, exposures cannot exceed 18 minutes in length.

An alternative which may prove very attractive in the long run would be to utilize X-LOCAL VERTICAL mode when observing objects within 60° of the orbit poles and to utilize X-POP mode when observing objects within 30° of the orbit plane. In the X-LOCAL VERTICAL mode with the Z-axis perpendicular to the orbit plane, the vertical axis of the inside-out-gimbal of IPS is very nearly a polar axis. In this case, most of the tracking may be accomplished with a 4°/min rate about this axis, with only small corrections being required in the other two axes. Such an orientation may indeed make it possible to maintain full stability accuracy while tracking at orbital rate.

3. Contamination

Contamination from the vernier thrusters is an important consideration when attitude holding and maneuvering is considered. Contamination from other sources (such as outgassing of Shuttle and the payload bay and water dumps) are also of critical concern to SUOT. Such contamination has three undesirable effects for astronomical telescopes: (a) thin films of contamination deposited on mirror surfaces may drastically reduce reflectivity in both the ultraviolet and the infrared regions of the spectrum, (b) column densities of molecules surrounding the spacecraft may be sufficiently high to impress molecular absorption features on the spectra of the cosmic sources being observed and (c) even very tenuous clouds of molecules or solid particles will add substantially to the background sky brightness of the day side of the orbit, and will critically affect the ability to observe faint objects for at least 60% of the orbital observing time.

The FDT has been informed of the current status of contamination control studies, but has not been able to assess in detail the adequacy of these for SUOT observations. However, it is clear that current limits on sky brightness and molecular column densities are marginal for SUOT and will be of continuing concern. It is probable that one of the dominant sources of contamination will be RCS thruster propellant. The discussion in the previous section indicates that propellant usage will be at least 1 pound per orbit, and may range as high as 18 pounds per orbit for short intervals. It is important that all aspects of how this propellant may affect SUOT observations be evaluated, in order that intelligent tradeoffs between maneuverability and contamination may be made.

4. Utilities

By "utilities" we mean Shuttle-provided power, communications, thermal cooling, and support of the payload crew.

The power requirements of SUOT are estimated to average 1 kilowatt. Although it is clear that SUOT will require more than the basic 50 kwh supplied to the payload by the Orbiter, the addition of a single power kit should supply SUOT for a full 30-day mission. A matter of much greater concern for 30-day missions is the problem of supplying power for the Orbiter itself. Data presented in the following section indicate that a substantial fraction of the payload for 30-day missions is consumed by power kits required mainly to support Orbiter and Spacelab power requirements. Every effort should be made to reduce these requirements.

It appears that the Shuttle communications system, though minimal, is adequate for SUOT. (See Section 3.8 of the BBRC Feasibility Study for an analysis of probable requirements.) Probably the most critical problem is the question of to what extent will the data gathered by SUOT be available for monitoring at the PSS. The currently proposed 10^4 kb/s link between the Spacelab Experiment Computer and the Orbiter Computer is a very restrictive constraint, and it is hoped that some improvement in this rate may be gained through improved computer technology in the early 1980's. Although the typical stellar astronomy instrument does not exceed this rate, the high priority planetary camera is an example where the 10^4 kb/s rate is easily exceeded. In this instance, we expect to obtain digital data from a 400 x 400 pixel array in a grey scale with 64 levels at a rate as high as 10 frames per second. This results in a data rate of 10 mb/s. Although this rate can be handled on the direct down-link, it cannot be channeled through the Orbiter computer to the PSS.

Some compromise must be made. Assuming the camera is being used for planetary science, the entire picture could be transmitted to the PSS only once every 100 seconds. This may be marginally satisfactory for monitoring scientific data, but, if one is concerned with monitoring the jitter in the IPS when a malfunction is suspected, this rate is obviously not satisfactory. It may then be proposed that only a 10 x 10 pixel square be transmitted 10 times per second for this purpose. Although most uses of the planetary camera may be achieved by providing it with a sophisticated control and processing computer, it is evident that expense to this experiment and to many others could be saved by an improved data link to the PSS.

A second and related area of concern is the problem of storing data onboard for later monitoring or for later comparison with new data. Again the planetary camera provides an urgent example. One of the Payload Specialist's more interesting objectives will be to detect transient events as promptly as possible. This is best accomplished by comparing the current data with data obtained 10 minutes or 30 minutes previously. No data storage device with the necessary capability is now planned for the payload data handling system. Although Polaroid-type photographs may help solve the problem, it would provide much greater detectivity to compare two video images directly. Such a system would allow computer-differenced or computer-enhanced data handling, for example. It is strongly recommended that storage devices be provided by the Spacelab or Orbiter data handling systems to make possible such comparisons between current data and previous data.

A third concern is whether or not computer-processed displays may be shown on the Closed Circuit TV (CCTV) system. For example, since it is possible to display video images of star fields on the CCTV, it would also be highly desirable to display a computer-constructed field from a star catalogue superposed on the real star field to speed the field identification process.

It is not expected that SUOT itself will exceed the thermal cooling capacity of the Orbiter, since it will have an operating temperature near 20°C maintained by heaters. However, a serious concern exists as to whether the cooling system at the PSS will permit the use of the sophisticated equipment required to permit truly autonomous operation of the payloads from the PSS. For example, the PSS shown in Figure 6 presumes the use of four CRT's, although it presently appears that this may exceed the cooling capacity at this location. Every effort must be made to provide sufficient cooling (or to find display devices requiring less power), since the ability to simultaneously display such items as data and commands and related star fields is a fundamental factor in whether effective instrument control and data monitoring can be performed at the PSS or whether these functions are to be carried out remotely from the POCR.

5. Payload Weight Considerations

NASA documents of February 1975 on Weights Chargeable to Payload (NASA-S-75-360) and on Mission Kits (NASA-S-75-457) make possible a detailed analysis of how the extension of mission duration beyond the basic 7-day duration will affect the total launch and landing weights chargeable to SUOT. Such an analysis has been carried out by Dr. T. R. Gull of Lockheed Electronics Company. He finds that payload weights for missions as long as 30 days are well within the 65,000-pound launch limit and the 32,000-pound landed limit. Of the basic 13,800-pound launch weight chargeable to SUOT for basic 7-day missions, about 8,400 pounds is due to the telescope itself and the remainder to such items as Spacelab components, the Payload Specialist Station, and electrical power kits. It should be considered that some of these latter weights would be shared by other payload experiments, since this is weight of basic equipment needed by all payload attached experiments. Thus, Guideline No. 8 (see Appendix A), which requires that SUOT constitute less than one-half a Spacelab pallet-only payload, is well satisfied. The growth of SUOT launch and landing weights as mission duration increases is shown in Figure 8.

Beyond the baseline number of four, additional crewmen do not seriously impact chargeable weights. Even for 30-day missions, adding a crewman increments the total weight by only 650 pounds. Thus, a 6-man crew could fly on a 30-day mission with 5000 pounds of landing weight available for other experiments. It

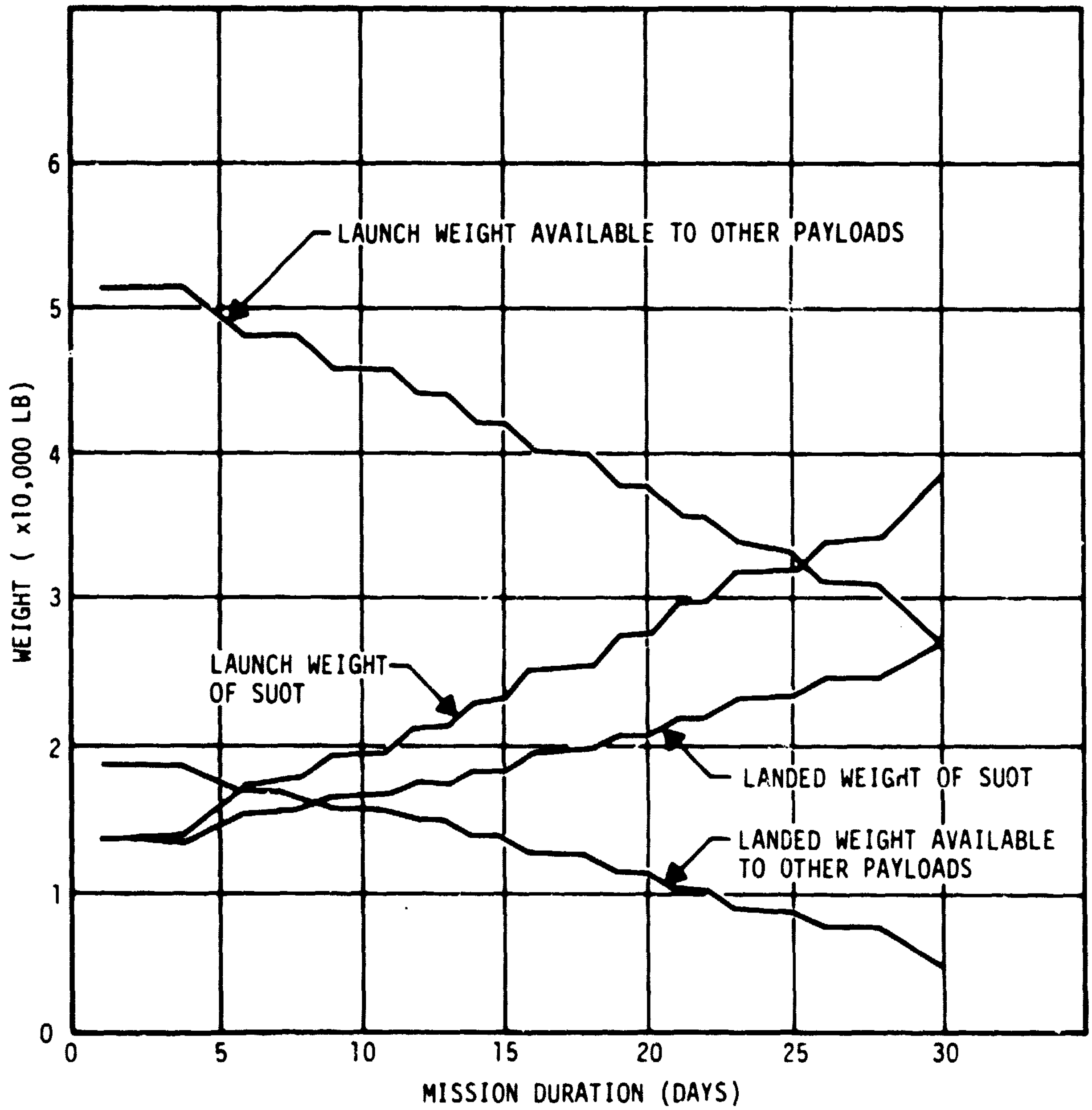


Figure 8. SUOT Payload Chargeable Weights Versus Mission Duration (Six-Man Crew)

should also be noted that a major portion of the 65,000-pound launch weight is always available for free-flyers. Nearly all astronomy pallet-mounted missions would be the most cost-effective if shared with free-flyer payloads.

A much greater impact on payload weights is due to electrical power supply kits. All power needs beyond a baseline of 1836 kwh is charged to payloads. Orbiter uses about 300 kwh each day, necessitating at least one additional kit weighing 1564 to 1877 pounds every 3 days after the initial 4 days of a mission. For a 30-day mission, one half the launch weight charged to payloads must be dedicated to electrical power kits. The facility definition team recommends that all means of energy-saving by Orbiter and its payloads should be examined. Substantial decreases in power needs will mean very substantial increases in science by the addition of more small experiments to an astronomy payload.

APPENDIX A

Guidelines for the SUOT Study

The following set of guidelines for this study was suggested by the GSFC study scientist. They were reviewed and adopted by the FDT with only minor reservations.

1. The SUOT will be operated as a Spacelab or Shuttle Sortie facility. Its possible use as a free-flying, automated satellite is not to be invoked.

2. The SUOT will be a general purpose, astronomical telescope. It should

   a. reflect foreseeable scientific requirements of a broad spectrum of astronomical users,

   b. be usable with a variety of focal-plane instruments,

   c. provide relatively simple and well-defined interfaces (such as optical, mechanical, thermal, electrical, and computational) for the general user, and

   d. provide a benign environment for astronomical instrumentation.

3. The SUOT will be programmatically flexible. It should

   a. be amenable to ground refurbishment and reflight as often as 2 to 3 times per year for a decade, and defined so as to make cost-effective use of that capability,

   b. allow cost-effective upgrading of its performance over its lifetime, and

   c. be capable of sharing a given flight with other disciplines - most especially with Solar Physics, High Energy Astrophysics or automated satellite deployment/ recovery flights - wherein orbiter orientation, mission timeline and resource allocation will be optimized to serve the needs of the total payload.

4. The SUOT facility concept will be driven by the requirement to optimize, within program constraints, operations efficiency so as to assure the return of as much high quality data as possible from each flight.

5. The SUOT will be usable as a national facility with focal plane instruments developed primarily by Principal Investigators.

6. The SUOT will be a relatively low-cost facility. At least one concept for SUOT will be defined within a cost target of $\$1 \times 10^7$ (1974 dollars), including all telescope-unique hardware and an initial set of focal plane instruments. More costly concepts may be considered, but it should be recognized that the probability of program implementation will be substantially reduced as costs approach or exceed $\$2 \times 10^7$.

7. In the definition of the SUOT, requirements for new technology development will be minimized. Currently understood design approaches and current technology will be used to the greatest possible degree. The results of previous telescope studies will be used where possible.

8. In terms of weight, volume and resource requirements, the SUOT will constitute the equivalent of one-half a Spacelab pallet-only payload or less for a 7-day flight.

9. The SUOT will be fully productive during spacelab flights of 7 days duration. The facility definition will assure that outgassing, thermal equilibration, etc., will not unduly hamper the use of the SUOT during 7-day missions. The SUOT will be capable of use on Spacelab flights as long as 30 days duration. The facility definition will carefully consider crew consummables and other resources required to extend mission duration from 7 to 30 days, and will assure that the weight penalties so incurred will not prevent the SUOT from being used in 30-day flights.

10. The SUOT will be capable of carrying and utilizing two or more focal plane instruments per flight so as to enhance mission reliability and flexibility.

11. The SUOT will utilize Shuttle-Spacelab-ASP resources where possible. The facility definition will seek to minimize any reliance on telescope-unique systems.

12. The SUOT will be consistent with Shuttle-Spacelab-ASP programmatic and technical constraints, including those related to payload center of gravity, safety, contamination, cross-interference with other payloads, payload integration, crew structure, telemetry, and communications.

13. The final SUOT definition will be the responsibility of NASA, taking into account the FDT study results, related engineering studies and program requirements. Issues of major controversy or issues with major programmatic impact may be resolved by the ASP project or by NASA Headquarters.

APPENDIX B

Limiting Magnitudes for SUOT Field Imagery

In Table B-1, we give an analysis of the relative capabilities of SUOT, the ST and the ground-based, 200-inch telescope for observations of point sources. Signal-to-noise (S/N) ratios based on photon statistics have been calculated, in most instances, for 30-minute exposures and 1000Å bandpasses. The night sky brightness is taken to be V = 23 mag/arcsec^2 for the space telescopes and V = 22 mag/arcsec^2 for the 200-inch, ground-based telescope. The day (sun-side) sky brightness in orbit is assumed to be V = 20 mag/arcsec^2. Both the sky and star energy distributions (per unit wavelength) are assumed to be constant across the bandpass. We assume an overall detection efficiency for the telescope and detector of 0.1 and that a V = 0.0 star yields 1000 photons/sec-cm^2-Å at 0.55μm at the telescope primary.

Problems of detector noise and detector saturation have been evaluated assuming an electrograph operating with an S-11 photocathode and L4 emulsion. It is assumed that 7 photoelectrons per square micron produce a density of one in this emulsion and that the uncooled photocathode produces instrument background fog at the rate of 0.001 density units per minute. It is found that the instrument noise is slightly stronger (a factor of 1.5) than sky noise for SUOT and considerably stronger (a factor of 4) than sky noise for ST and, therefore, affects limiting magnitudes. However, since detector noise can be reduced by a factor of about 100 by cooling, it is assumed that this noise can be effectively eliminated; therefore, it is not included in Tables B-1 and B-2.

We find that for isolated point sources, SUOT and the 200-inch have equal S/N ratios at V = 24.5 under the assumed conditions, and that at fainter magnitudes SUOT is faster than the 200-inch. For faint point sources in crowded fields or superposed on a bright background (for example, stars in globular clusters or nearby galaxies), SUOT will have an insuperable advantage over any ground-based instrument by virtue of its faint limiting magnitude, its high angular resolution and its good contrast fidelity. Suot will have an even more significant advantage over the 200-inch for isolated point sources in the near infrared (0.6-1.0 μm), where the orbital sky will be 2-4 magnitudes fainter than on the ground.

The ST is the fastest of the three instruments if field area is not a factor. However, if field area is a factor (as is the case for observation of nearby galaxies, for survey-type observatory, etc.) then SUOT is significantly faster. At V = 26, the ST/SUOT ratio of S/N is 3.8; thus, SUOT can reach the same S/N as ST by exposing 14 times as long. However, since SUOT has 100 times the field area of ST, it is faster by a factor of seven in conducting large area surveys for point sources to V = 26. This comparison becomes even more favorable for SUOT as one goes to brighter magnitudes, at which the contribution of sky background noise becomes relatively less important. For example, at V = 25, SUOT can reach the same S/N as ST by exposing 11 times as long, and hence is 9 times more efficient than ST in surveying large areas for point sources to V = 25.

For extended objects, S/N may be increased for any observing configuration simply by increasing the sample area. S/N calculated using the assumptions given above for a sample area 2 arcsec in diameter is given for V magnitudes in the first part of Table B-2. Other parameters remaining constant, S/N for a fixed angular area scales as the diameter of the primary. Because a number of the anticipated applications of SUOT will include surface photometry in the near infrared, we also give S/N for a bandpass centered near 1 μm. The airglow brightness for Palomar here is taken from 200-inch spectrophotometry. Orbital sky brightness has been extrapolated from V = 23 mag/arcsec^2, assuming that the spectral energy distribution of the orbital sky is identical to the Sun's, since SUOT and ST will operate well above the primary OH-emitting layers. We note that SUOT can be readily equipped with a focal reducing camera to enable it to reach faint surface brightnesses with bare photographic plates or other detectors whose application would otherwise be precluded by threshold or readout-noise problems.

At high brightness levels, SUOT can achieve S/N = 100 in 30-minute exposures for 0.3 arcsec resolution elements on extended objects with V = 17.0 mag/arcsec^2, a value typical of moderately bright planetary nebulae, for example.

To reach the faintest possible limiting magnitudes on spectrally continuous sources, space telescopes can employ the entire spectral range available to their detectors. Ground-based telescopes are limited to much smaller spectral ranges by airglow and man-made radiation, as well as by atmospheric absorption. Examples of S/N ratios for both SUOT and ST employing a 5000Å bandpass are given for point sources in Table B-1. Corresponding increases in S/N would apply to Table B-2.

TABLE B-1

LIMITING MAGNITUDES FOR POINT SOURCES

QUANTITY		SUOT	ST (2.4m)	200-inch
Mirror Area	(cm^2)	6892[a]	39,700[a]	184,500
Photoelectrons/sec/1000Å/ 25 mag (V)		0.0689	0.397	1.84
Focal Ratio		15	24	3.5
Plate Scale	(arcsec/mm)	13.75	3.58	11.60
Image Diameter (60% encircled energy)	(arcsec)	0.3	0.15	2.0
" " "	(μm)	21.8	41.9	172.4
Image Area	($arcsec^2$)	0.0707	0.0177	3.142
Image Area	(μm^2)	374.	1379.	23347.
Night Sky Magnitude Per Image Area		25.88	27.38	20.76
Night Sky Photoelectrons/Image Area/30 min/1000Å		55.1	79.8	164500.
Night Sky Photoelectrons/μm^2/ 30 min/1000Å		0.147	0.058	7.0
Star Photoelectrons/Image Area/30 min/1000Å[b]	24 mag	187	1077	4892
	25 "	74	429	1987
	26 "	30	171	791
	27 "	12	68	315
Star S/N/30 min/1000Å (night)	24 "	10.8	30.6	12.1
	25 "	5.4	17.7	4.9
	26 "	2.5	9.4	1.9
	27 "	1.1	4.5	0.8
Sky Density/30 min/ 1000Å with L4 emulsion		0.021	0.008	1.0

NOTES:

a. Assumes 0.35 central obscuration.

b. Assumes 60% total energy within image area.

Table B-1 (continued)

QUANTITY		SUOT	ST (2.4m)	200-inch
Star S/N/30 min/5000Å (night)	24 mag	24.1	68.4	--
	25 mag	12.1	39.6	--
	26 mag	5.6	21.0	--
	27 mag	2.4	10.1	--
Sky Density/30 min/5000Å with L4		0.1	0.04	(5.1)
Day Sky Photoelectrons/ Image Area/30 min/1000Å		873	1265	--
Star S/N/30 min/1000Å (day)	23 mag	10.0	37.4	--
	24 mag	4.2	17.9	--
	25 mag	1.7	7.9	--
	26 mag	0.7	3.3	--
Sky Density/30 min/1000Å with L4 (day)		0.33	0.13	--

TABLE B-2

LIMITING MAGNITUDES FOR EXTENDED OBJECTS

QUANTITY	SUOT	ST (2.4m)	200-inch
image element diameter (arcsec)	2	2	2
image element area/point source area	45	180	1
image elements per field	$8x10^5$	$7x10^3$	$8x10^5$
<u>S/N at 0.55 μm</u>			
sky brightness (mag/arcsec^2)	23	23	22
S/N/30 min/1000Å			
23 mag/arcsec^2	29	69	105
24 "	13	31	44
25 "	5.4	13	18
26 "	2.2	5.3	7.2
<u>S/N at 1.0 μm[a]</u>			
sky brightness (mag/arcsec^2)	23.5	23.5	19.5
S/N/30 min/1000Å			
23 mag/arcsec^2	19	45	20
24 "	8.7	21	8.2
25 "	3.7	8.9	3.2
26 "	1.5	3.6	1.3

<u>NOTE</u>:

a. The source flux at 1.0 μm has been decreased relative to that at 0.55 μm by a factor 0.32, corresponding to the flux distribution of an A0 V star.

APPENDIX C

Capability of the Far-UV Spectrograph

Since the main thrust of Section III.B (Scientific Objectives) deals with the study of absorption lines produced by the interstellar gas, our discussion of the principles which govern instrumental capabilities will adhere to this context. For other fields of research, such as stellar atmospheres, some modification and generalization of the arguments will likewise yield a perspective on the attainability of certain goals.

a) Sensitivity

i. Basic Equations

A photoelectron count rate per unit frequency interval

$$N_\nu = \frac{\pi F_\nu}{h\nu} \left(\frac{R_*}{d_*}\right)^2 \frac{\pi}{4} (1 - \beta_o{}^2) \quad a^2 \varepsilon_\lambda \quad Hz^{-1} s^{-1} \qquad (1)$$

will be registered by a telescope - spectrometer having

β_o = secondary mirror diameter divided by primary mirror diameter

a = primary mirror diameter

ε_λ = product of mirror reflectivities, grating efficiency and detector quantum efficiency which views an unreddened star with

R_* = radius of the star

d_* = distance to the star

πF_ν = surface continuum flux (in ergs cm^{-2} $Hz^{-1} s^{-1}$) at a frequency, ν.

Interstellar reddening will reduce the flux by a factor

$$R_\nu = 10^{-0.4 E_{B-V} \left(\frac{E_{\lambda-V} + A_V}{E_{B-V}}\right)} \qquad (2)$$

where E_{B-V} is the B-V color excess. A_V is the absorption at V wavelengths and is generally assumed to be 3.0 E_{B-V}. $E_{\lambda-V}$ is the additional absorption which occurs at shorter wavelengths λ. To express R_ν in terms of the total column density of hydrogen N_H (in all forms: atoms, molecules, or protons) we may replace E_{B-V} by $N_H/(7.5 \times 10^{21}\ cm^{-2})$.

For unsaturated absorption lines, we may determine the column density N of atoms or molecules from the measured equivalent widths W_ν from the relation

$$N = W_\nu\ mc/\pi e^2 f. \tag{3}$$

If the continuum level is smooth and well defined, photoelectron statistics will limit the accuracy of the measurement to an error (at one standard deviation) of $\sigma(W_\nu)$ given by

$$\sigma(W_\nu) = (\nu\ \Delta v/cF_\nu t)^{1/2} \tag{4}$$

where t is the integration time and Δv is the doppler velocity passband over which one must measure W_ν (equal to either the actual profile velocity spread, uncertainty in expected radial velocity, or instrumental resolution, whichever is greater). If we combine equations 1, 3 and 4, we find the error in column density deduced from an unsaturated line is

$$\sigma(N) = 3.38 \times 10^{-7} \frac{d_\star}{a\lambda f R_\star} \left[\frac{\Delta v}{R_\nu\ F_\nu\ \varepsilon_\lambda t\ (1-\beta_\lambda^2)}\right]^{1/2} \tag{5}$$

For an assessment of the versatility of an observing instrument under some specified conditions, it is useful to compare $\sigma(N)$ with N_S, the representative column density for which an absorption line becomes saturated. While one may work with saturated lines in deriving abundances of various species, the results become increasingly inaccurate and more dependent on assumed velocity distributions as the saturation becomes stronger. If we adopt N_S to be the column density where one attains a central optical depth of unity for a gaussian velocity profile with a velocity dispersion of $b/\sqrt{2}$, we find

$$N_S = 66.7b/\lambda f. \tag{6}$$

A good figure of merit for observations is expressed by the ratio

$$N_s/\sigma(N) = 1.98 \times 10^8 \frac{bR_* a}{d_*} \left[\frac{R_\nu F_\nu \varepsilon_\lambda t (1-\beta_o^2)}{\Delta v}\right]^{1/2} \quad (7)$$

which may be viewed as either a representative "dynamic range" for meaningful observations of line strengths, or as the signal-to-noise ratio for measurements of moderately strong (but unsaturated) lines under certain observing conditons.

ii. Representative Numerical Calculations

For an integration time of 30 minutes with $\beta_o = 0.3$, a = 100 cm, b = 5 km s^{-1} and $\Delta v = 4.24b$ (giving an integration of W_ν over $\pm 3\sigma$ of the gaussian velocity profile), Equation (7) reduces to

$$\log N_s/\sigma(N) = 4.66 + 0.5 \log F_\nu \varepsilon_\lambda - 2.67 \times 10^{-23} cm^2 N_H \left[\left(\frac{E_{\lambda-V}}{E_{B-V}}\right) + 3.0\right]$$

if we adopt for a moderately difficult case the observation of a hot star having a value of 6×10^9 for the ratio of d_* to R_* (or 0.2 if R_* is expressed in terms of 10^{11} cm and d_* in kpc). This corresponds, for instance, to a B1 IV star at 1 kpc or a B1 I star at 4 kpc (the corresponding V magnitudes of these stars would range from about 6 to 8, depending on reddening).

For F_ν, we shall adopt the fluxes tabulated by Carbon and Gingerich for T_e = 25,000° K and log g = 4.0. As presently envisioned, the 1-meter facility will have a configuration very similar to that of the Copernicus instrument (i.e., two reflecting surfaces, one grating and a photocathode). Thus, except for the factor 2 loss at t[illegible]trance slit of the Copernicus spectrometer, probably t[illegible] reliable indication for realistic value of ε_λ can be tak[illegible] from the measured efficiencies of this system at various wavelengths. Values for $E_{\lambda-V}/E_{B-V}$ are taken from OAO-2 and Copernicus observations.

TABLE C-1

Parameters Used for Signal Quality Calculations
for Far-UV Spectrograph

λ (Å)	F_ν	ε_λ	$(E_{\lambda-V}/E_{B-V}) + 3.0$
940	1.26 (-3)	5.6 (-4)	15.6
955	3.12 (-3)	8.9 (-4)	15.2
965	3.54 (-3)	1.2 (-3)	14.9
975	1.56 (-3)	1.8 (-3)	14.7
1000	3.86 (-3)	5.0 (-3)	14.0
1015	3.71 (-3)	6.8 (-3)	13.6
1030	2.71 (-3)	8.6 (-3)	13.2
1050	3.80 (-3)	1.1 (-[illegible])	12.7
1100	3.73 (-3)	8.7 (-3)	11.4
1190	3.56 (-3)	4.0 (-3)	10.0

The behavior of log $[N_S/\sigma(N)]$ with λ was computed using Equation (8) and the numbers in Table C-1; the results are shown in Figure C-1 for three representative values of N_H. For the observing conditions here, reasonably accurate conclusions could be drawn from observations above about 940Å for low color excesses, while one must go above 1040Å when the reddening reaches 0.40 magnitudes. With these graphs we may easily evaluate the behavior of log $[N_S/\sigma(N)]$ for other values of t, $R_\star$, $d_\star$, b, etc., by noting how these parameters scale in Equation (7).

Equation (6) indicates that near 1000Å $fN_S = 3 \times 10^{12}$ cm^{-2} when b = 5 km s^{-1}. Hence, the sensitivity (one sigma error) in measuring weak lines for $N_H = 10^{21}$ cm^{-2} (middle curve in Figure C-1) corresponds to about $3.5 \times 10^{-11}/f$ times the total hydrogen abundance (f-values for permitted transitions typically range from around 0.001 to several tenths). Generally speaking, this puts within easy grasp those elements having an interstellar abundance greater than about 10^{-8} that of hydrogen, provided they have transitions in our wavelength range from favored ion states.

Up to now, we have examined the performance, as a function of wavelength, for an imaging spectrograph measuring a moderately faint star. We now focus our attention on a single wavelength, let us say 1030Å, where efficiencies are good, and question how many stars are available which can yield results whose quality exceeds a given amount. Again if we think in terms of a 30-minute integration time and the telescope parameters specified earlier, we can define $N_S/\sigma(N)$ as a function of V magnitude, E(B-V) and spectral type. Instead of using a model atmosphere to define F_ν, we shall rely on empirical results from Copernicus

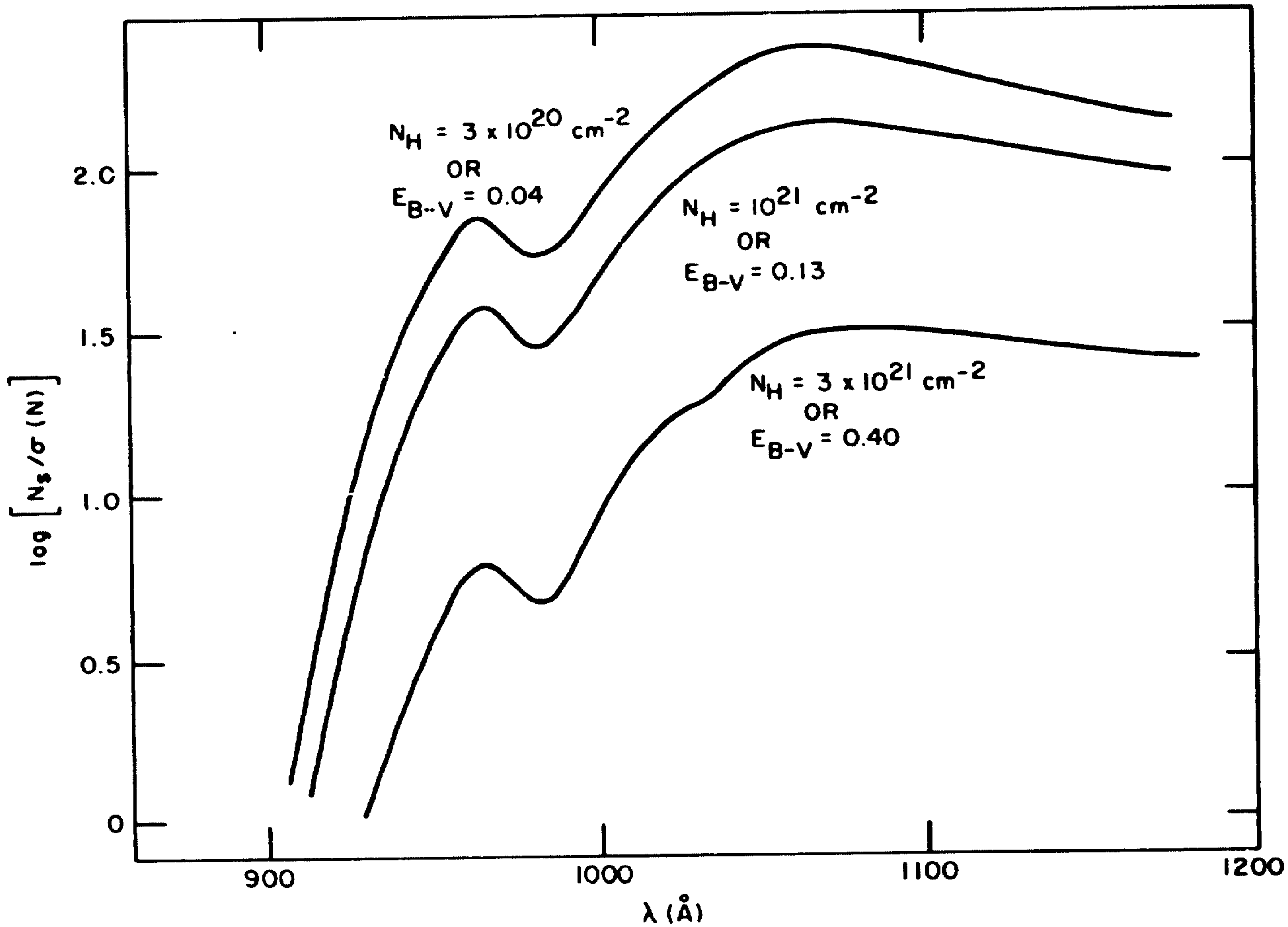


Figure C-1. Far-Ultraviolet Spectrograph, Estimated Signal Quality Versus Wavelength observations of observed count rates times $10^{0.4V}$ for various spectral types, after corrections for reddening. Stars with low projected rotation velocities are seen to have sharp and strong photospheric features which introduce confusion in the analysis of absorption by interstellar gas. Hence, in counting the available stars in the sky, only those which are known to have v sin i $\gtrsim$ 100 km s^{-1} are included.

Figure C-2 gives a cumulative number distribution of hot stars which should yield results whose $N_S/\sigma(N)$ should exceed the value specified on the abscissa scale. Owing to the incompleteness of the catalogues, especially the compilations of v sin i, the curve levels off on the left-hand side. The curve tells us, for instance, there are about 60 stars which could give us $N_S/\sigma(N) > 300$ in a half-hour exposure, while 175 stars would give us $N_S/\sigma(N)$ of at least 100 over the same integration time.

iii. Sensitivity to Diffuse Emission Lines (from planets, comets, interplanetary gas, etc.)

An emission line brightness of 1 Rayleigh corresponds to 1.87×10^{-6} phot $cm^{-2}s^{-1}$ $arcsec^{-2}$. For a spectrometer entrance slit width corresponding to an angle Δi and a source angular length (or spectrometer acceptance angle perpendicular to the dispersion direction, whichever is less) Δj, we find 1 Rayleigh gives a photoelectron count rate

$$N = 1.87 \times 10^{-6} \frac{\pi}{4} (1-\beta_0^2)\, a^2 \epsilon_\lambda \;\; \Delta i \, \Delta j \;\; (\Delta i,\ \Delta j \text{ in sec}) \qquad (9)$$

integrated over all wavelength channels. For numerical values given in the beginning of the previous section, we fi

$$N = 1.07 \times 10^{-5}\ \Delta j \text{ at } \lambda = 1216\text{Å (Lyman-}\alpha)$$

and $N = 2.94 \times 10^{-5}\ \Delta j$ at $\lambda = 1050$Å (near the argon emission lines)

if $\Delta i = 0.2$ sec.

b) Wavelength Resolution

The shape of the focused spectrum image combined with the angular configuration of incident and diffracted beams with respect to the grating are the ultimate factors which govern the wavelength resolution of a spectrograph. If optical imperfections in the main telescope and image motions enlarge the apparent angular diameter of a star to 0"2, without aberrations the image size will be $9.7 \times 10^{-7}\ \ell$, where ℓ is the focal length of the telescope. For a 1-meter f/15 telescope the image will be 15 microns in diameter, which is smaller than (or, at best, comparable to) the resolution limit of photoelectric imaging detectors in the far ultraviolet. Hence, the minimum resolvable element size for the

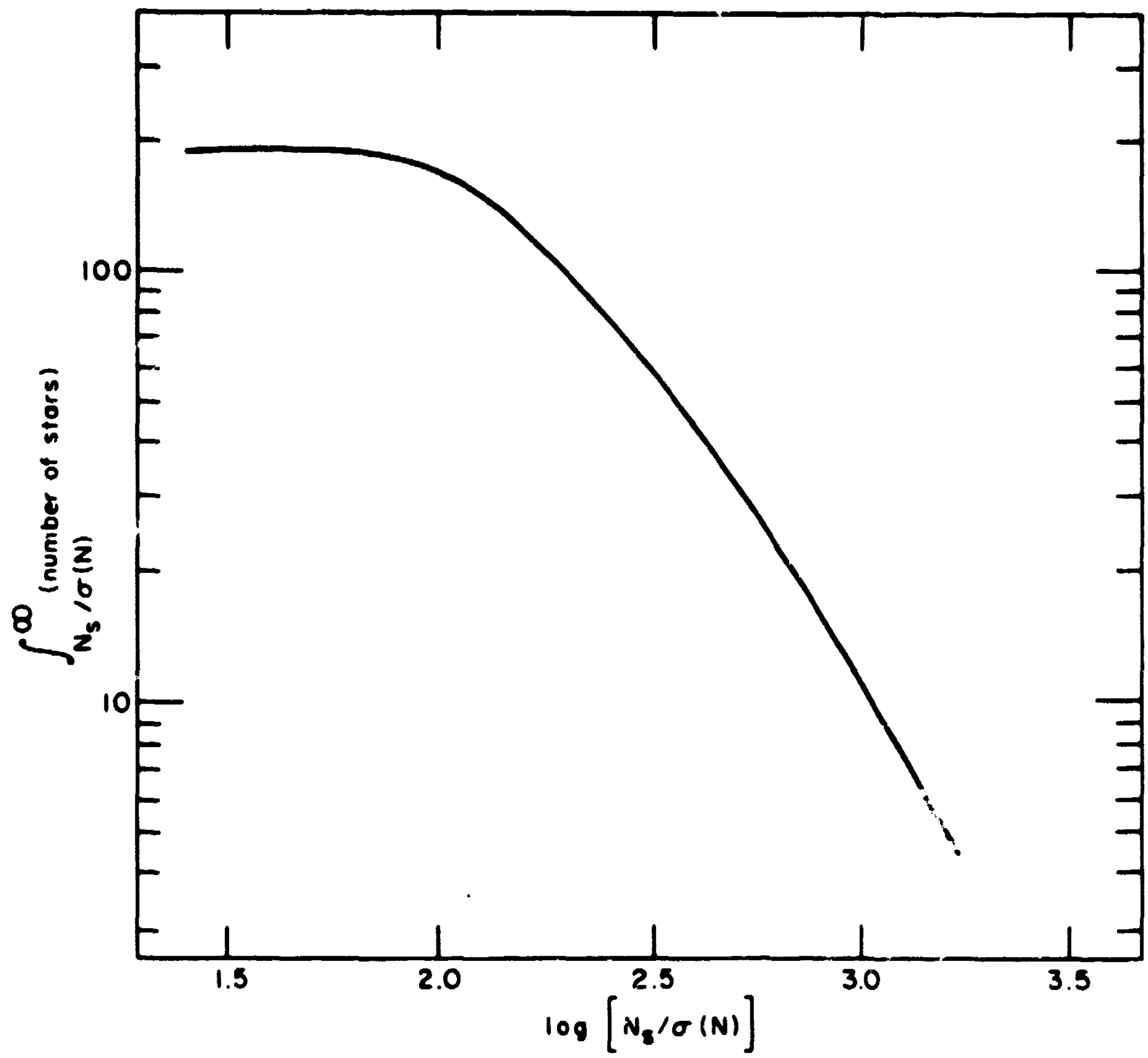


Figure C-2. Far-Ultraviolet Spectrograph, Cumulative Available Number of Hot Stars Versus Signal Quality detector replaces the aberrationless image size as a driver of spectral resolution.

We can increase the resolving power of the spectrograph by enlarging the diameter of the Rowland circle, since the linear resolving power of the detector is fixed. The largest diameter which will probably fit behind the telescope is 1.5 meters. With the f/15 beam, this results in a grating whose dimensions must be 10 cm cos i high (perpendicular to the dispersion plane) and 10 cm wide, where i is the angle of incidence. If we adopt 50 μm as a conservatively large detector element size, the resolving power is $\lambda/\Delta\lambda$ = (1500 mm/0.05 mm) (sin i + sin r) sec r, where r is the angle of diffraction from the grating normal. To obtain a reasonable blaze efficiency, we require i not to be greatly different than r. Also, if we wish to have reasonable control over aberrations, we should avoid excessively large angles.

Figure 4 of the main text shows one possible configuration for the spectrograph which represents a reasonable compromise between awkard angles and any sacrifice in resolution. The spectral coverage ranges from 900Å, just below the Lyman series limit, to around 1220Å, which is high enough to include the Lyman-α transition at 1216Å. The grating is ruled with 3600 lines/mm. and the spectrograph works in 3rd order. We may avoid interference from other orders: 4th order light at the position of 3rd order 1220 is below the Lyman limit and 2nd order radiation at the short wavelength limit can be eliminated by using a photocathode material insensitive to photons greater than 1350Å.

For a spherical concave grating whose radius of curvature of 1500 mm equals the diameter of the Rowland circle, the image will be elongated perpendicular to the dispersion direction by astigmatism given by

$$y_1 = (100\text{mm})\ (\sin i \tan i + \sin r \tan r) \cos r \cos i \quad (10)$$

where the 100 mm represents the height of the grating rulings. These elongated images will have some curvature produced by coma, resulting in a cusp shaped spectrum line. The distance y_2 along the dispersion direction from the cusps to the center is given by

$$y_2 = \frac{(100\text{mm})^2\cos^2 i}{8\ (1500\text{mm})} \left\{ \sin i \tan^2 i - \sin r + \frac{\tan r}{\cos r} \left[1 - \frac{y_1}{(100\text{mm}) \cos i} \right]^2 \right\}. \quad (11)$$

c-2

The center of the cusp spectrum line will be broadened by 3rd order spherical aberration given by

$$y_3 = \frac{(100\text{mm})^3}{8(1500\text{mm})^2} \text{ (sin i tan i + sin r tan r) cos r.} \qquad (12)$$

With proper sampling of the spectrum in the image plane, astigmatism and coma have no impact on resolution; on the other hand, spherical aberration actually widens the image and reduces the resolution. Values for r, $\lambda/\Delta\lambda$, y_1, y_2 and y_3 for various wavelengths along the circle are given in Table C-2.

TABLE C-2

Image Aberrations in Far-UV Spectrograph

λ (Å)	r (degrees)	λ/Δλ (50 μm)	y_1 (mm)	y_2 (mm)	y_3 (mm)
900	16.8	3.0×10^4	50.6	0.168	0.038
950	20.1	3.3×10^4	52.3	0.144	0.039
1000	23.4	3.5×10^4	54.2	0.121	0.041
1050	26.9	3.8×10^4	56.4	0.095	0.042
1100	30.4	4.1×10^4	58.8	0.069	0.044
1150	34.0	4.5×10^4	61.4	0.044	0.046
1200	37.9	4.9×10^4	64.2	0.016	0.048

Note: i = 43°

Unacceptably large values for y_1 appear over the whole wavelength range. To reduce the astigmatism, we propose to reduce the radius of curvature of the grating perpendicular to the dispersion by a small amount, giving us a torroidal surface. If the compensation is complete at any one wavelength, we will be unable to disentangle the smearing by coma, resulting in a serious compromise in wavelength resolution. Hence, the compensation for astigmatism should be nearly complete at the short wavelength end, which leaves about 14 mm of remaining astigmatism for the longest wavelengths. For all but the shortest wavelengths, the spectrum width may somewhat exceed the width of conveniently available detector strips. Fortunately, the optical efficiency of the telescope and spectrograph is relatively large at the longer wavelengths (see Figure C-1), and, hence, the loss of flux will tend to reduce the disparity of exposure rates at short and long wavelengths.

The y_3 term represents the spread of the image at the paraxial focus. Improvement by approximately a factor of 4 can be realized if the image plane is repositioned at the circle of least confusion, just in front of the paraxial focus.

c) Possible Detectors

In the introductory remarks, it was made clear that the photons must have direct access to the photoemissive surface, without any intervening transmission elements such as a cathode face-plate. Opaque photocathodes with magnetic focusing or micro-channel plates followed by proximity focusing are two possibilities for accomplishing our objective. Actual detection of electrons may occur with either a charge-coupled detector, reticon or ranicon. At present, it is not clear which of the possible combinations is the best choice for the spectrograph.

Whichever system is adopted, it is clear that we cannot cover the entire spectral range with a single detector. It would be reasonable, however, to envision a linear chain of devices along the Rowland circle. There would probably be unavoidable gaps between these detectors. If, for instance, the gaps were 1/3 the length of each device, one could expose 2/3 of the complete spectrum in one exposure. After moving the detector array along the Rowland circle by a small amount, the remaining pieces (1/3) of the spectrum could be covered with some overlap with the previous exposure. In general, we should think of two exposures per object if complete wavelength coverage is desired.

APPENDIX D

Capability of the Precisely Calibrated Spectrophotometer - Polarimeter

For the purposes of this discussion we will adopt the following simple model system. The telescope will have an aperture of 1 meter and an obscuration ratio of 0.33, which results in an effective area of 7×10^3 cm^2. The overall responsive quantum efficiency of the system will be taken to be 0.05, which assumes three MgF_2 coated aluminum reflections at 90% each, a grating efficiency of just under 70%, and a detector quantum efficiency of 10%. The sky brightness at λ4250 (B) in magnitudes per square arc second will be taken to be 23.0 on the night side of the orbit and 20.0 under solar illumination, and the maximum integration time on any one object per orbit will be taken to be 30 minutes. We shall take "high precision spectrophotometry" to imply bandpasses of 10Å, and shall assume that during a typical integration at least 10^4 photons will be detected in each channel, in order that the photometric precision not be limited to worse than 1% by the photon statistics. This should not be construed to be a guarantee of 1% precision as there are likely to be other factors beyond photon statistics which will limit precision. Furthermore, both of these restrictions may be relaxed under conditions defined by the particular scientific program. Within the framework of this model system, we then require a flux at the telescope of 1.58×10^{-3} photons $cm^{-2}sec^{-1}Å^{-1}$, in order to accumulate 10^4 counts in a single channel during a single orbit. Figure D-1 shows the expected fluxes in these units from various sources.

A number of conclusions are immediately apparent from Figure D-1. First, even if the brightness of the sky due to the scattering of sunlight from materials in the immediate vicinity of the Shuttle Orbiter is considerably worse than the current estimate of B = 20m/sq arc sec, the sky background will not represent an important limit on high-precision spectrophotometry, so long as entrance apertures of less than about 3 arc sec diameter can be used. Second, if entrances of only 1 arc sec can be used, then, by relaxation of the precision criterion of 10^4 counts/channel/orbit, by the summing of channels, by multiple orbit exposures, or by some combination thereof, the system can be pushed several magnitudes fainter than the high-precision limit and remain insensitive to the sky brightness. Thus, it would seem reasonable to expect that the spectrophotometric equipment on the SUOT would be intensively used throughout the daylight portion of the orbit and would share a typical mission with instrumentation which requires dark sky, e.g., a direct camera or a broad-band or extended area filter photometer. Thus, in the discussions following, we will assume that two 30-minute exposures can be made during each orbit and that the dark part of the orbit will be left to an alternate instrument which requires it.

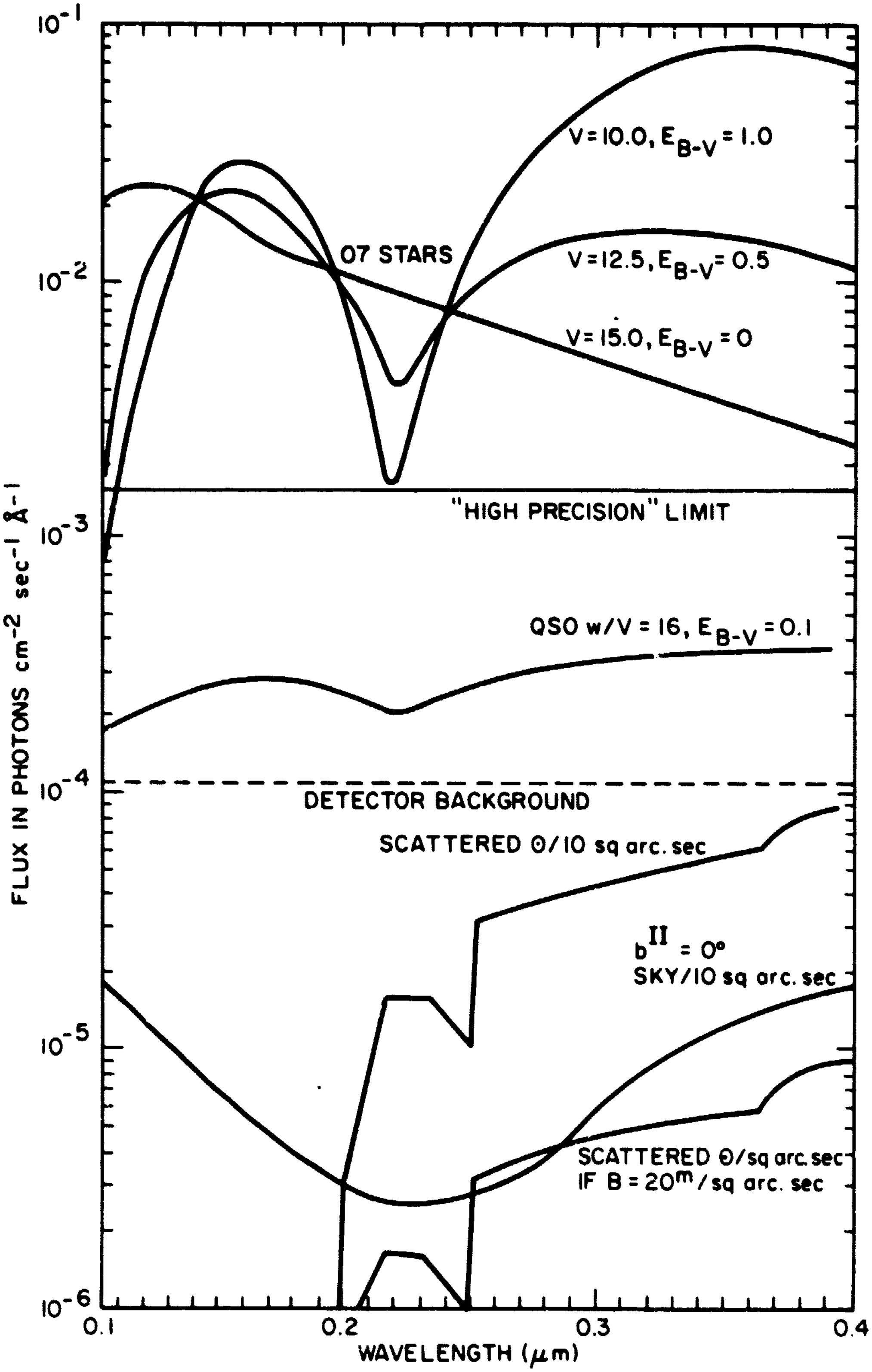


Figure D-1. Precisely Calibrated Spectrophotometer-Polarimeter, Expected Fluxes from Various Sources Versus Wavelength

A third important point illustrated by Figure D-1 is that a high degree of multiplicity of detectors is greatly desirable. The precision limit of Figure D-1 is set by requiring 10^4 counts in a single channel in a 30-minute exposure. For every 10 wavelengths which must be measured by a single detector, the limiting magnitude decreases by at least 2.5 magnitudes, and perhaps more, since adjustments in the wavelength of a detector require time not only to make but also to calibrate. Fortunately, detectors do exist which have been, or probably can be, space qualified and which can be fabricated in arrays such that virtually the entire spectrum within the useful blaze of a dispersing element can be covered simultaneously, or nearly so, in 10Å chunks. These possibilities are discussed in Section V.C. We will thus assume that all of the spectrum within a range of about 2500Å will be covered in each 30-minute exposure.

One final point bearing on measurability limits is that of detector background. The experience with the OAO-2 has shown that the background levels in detectors in space are many times the levels of the same detectors in the laboratory. This appears to be the result of the high energy particle environment in space, and, in particular, to be largely due to the fluorescence and phosphorescence of photomultiplier windows, since the phenomenon is greatly suppressed in far-ultraviolet, windowless detectors. The OAO-2 results apply to standard photomultipliers with large (e.g., several square-centimeters) window-photocathode areas used in the standard exit aperture-Fabry lens configuration of ground-based photometry. The levels often amounted to many tens of counts per second. If the phenomenon is directly related to the area of the detector, then a multichannel array directly in the spectrometer focal plane would also help to reduce the detector background per channel to acceptable levels. If we can assume a detector of area 2 mm^2, e.g., a single 1 mm x 2 mm channeltron, the detector background level can be estimated from OAO-2 data and plotted in the units of Figure D-1. The OAO-2 count rate was about 40 counts/sec/cm^2 of cathode in photometer S3 in orbits avoiding the South Atlantic Anomaly (SAA), and greater by at least 100 during and for many minutes after passage through the SAA. Take, as typical, 400 counts/cm^2, then per angstrom and per cm^2 of the 1-meter primary of the SUOT, this gives for our 10Å wide small detector a rate of 1.1×10^{-4}, which is plotted by a dashed line in Figure D-1. Since this is perhaps an optimistic estimate, somewhat greater than the pessimistic estimate of sky background contribution, it would probably be prudent to require the data system to include the possiblity of object-background chopping.

In addition to the photon flux limits on the capabilities of the SUOT spectrophotometer, it is necessary to consider the number of potential targets. Although surveys to the ultraviolet flux limits considered here are nonexistent, extrapolations can be made from OAO-2 data which are derived from the 3.3×10^{-2} photons $cm^{-2} sec^{-1} Å^{-1}$ limit of the OAO-2 photometer. Figure D-2 shows the integral luminosity function, i.e., the log of the number of objects of a given type with fluxes at 1550Å greater than the abscissa value, for several classes of interesting objects. Inspection of this graph shows that we can expect to make high-precision measures on many scores of objects in most classes.

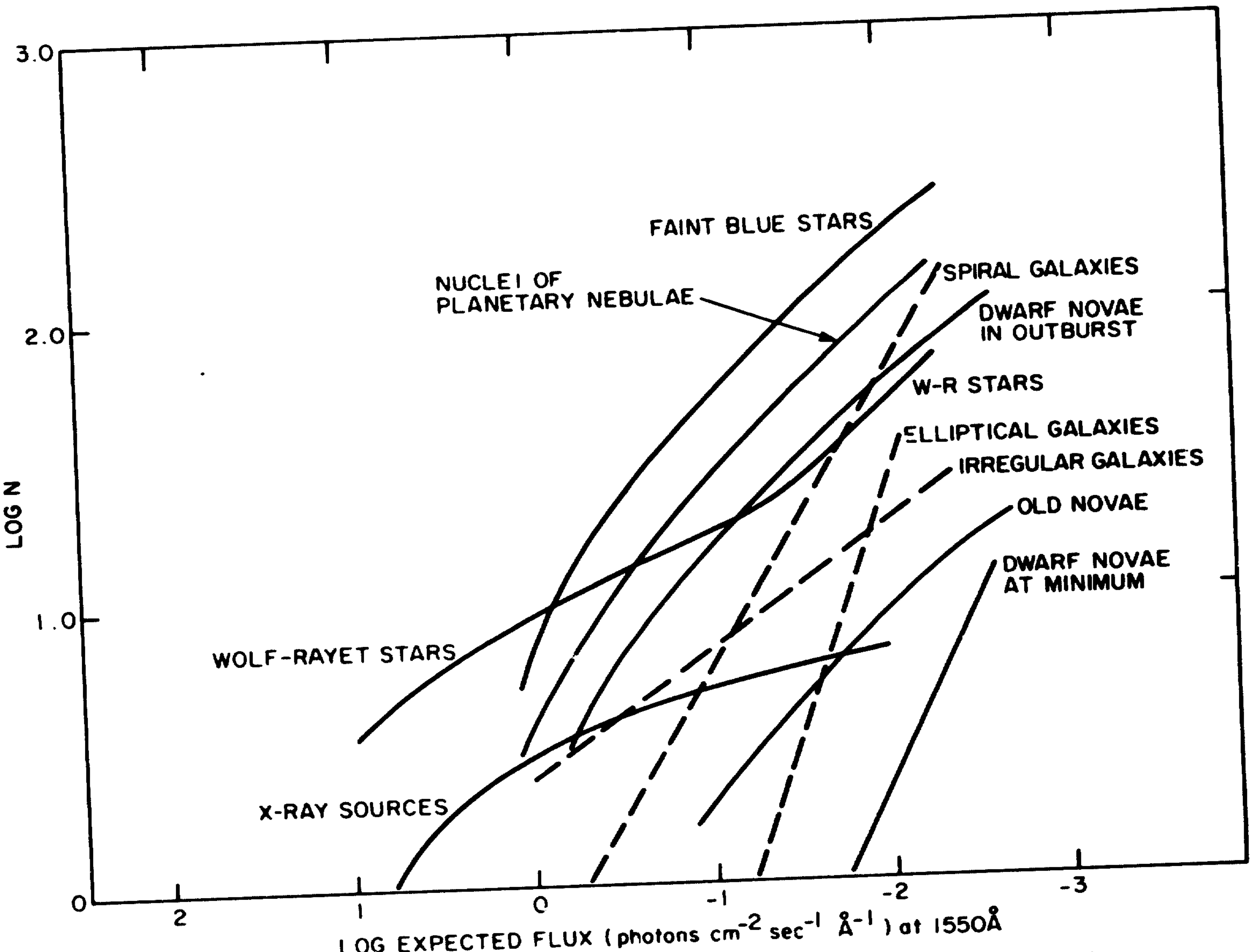


Figure D-2. Precisely Calibrated Spectrophotometer-Polarimeter, Cumulative Object Count Versus Expected Flux at 1550Å

APPENDIX E

Typical Operational Event Sequence

In Section VI.C a concept for control and data management is described. Here we exemplify application of this concept by following through the time-line of a data acquisition sequence. In Table E-1 are listed the major activities that occur during an observing sequence giving simultaneous use of the precisely calibrated spectrophotometer (PCS) and the direct imaging camera (DIC). The science involved is (a) absolute spectrophotometry of some object such as a Seyfert galaxy, and (b) in-depth direct imaging exploration in the vicinity of this galaxy for objects such as QSO's or faint clusters of galaxies. (See Section IV.D for further explanation of this dual operation.)

Before launch, a complete observing program has been detailed by scientists involved in this specific mission. Coordinates of all potential program objects and sensor positions to locate guide stars are assumed to be stored in computer memory. Field verification charts and other observing aids have been compiled and are carried aboard Shuttle for use by the scientists flying as Mission and Payload Specialists during this mission.

The left-hand operator (usually, but not necessarily, the Mission Specialist) initiates each observing sequence, coordinating Orbiter pointing maneuvers with SUOT pointing manuevers. It is assumed that 900-pound thrusters are used to provide rapid orbiter maneuvering rates (1/2° per second) and that the brakes on the SUOT mount must be locked at any time the thrusters are fired. However, since the thrusters operate for short intervals, only at the beginning and end of pointing maneuvers, we assume that the SUOT telescope can be unlocked, slewed, and relocked while the orbiter maneuver is underway. If slower orbiter rates are used, then the vernier thrusters may be used, and there will probably be no restrictions at all on simultaneous IPS slewing and orbiter maneuvering.

Initial pointing after a maneuver is expected to be accurate to a few tenths of a degree. It is expected that the IPS star trackers will then lock on to preselected guide stars and define pointing to a few arc seconds (see Special Note at end). The focal plane guide probes for the main telescope, having been positioned during the slew, now lock on their preselected guide stars and signal their readiness to begin the exposure. If any ambiguity arises as to the identification or suitability of guide stars, the SUOT Field Viewing Monitor is brought into use to confirm proper telescope pointing and to relocate suitable guide stars.

TABLE E-1

ILLUSTRATIVE SUOT OPERATIONAL EVENT SEQUENCE

TIME (MINUTES)	SUOT CONTROL	INSTRUMENT CONTROL
0		Terminate exposure N-1.
	Secure SUOT and IPS for maneuver.	Secure instruments for maneuver.
	Initiate Shuttle maneuver.	Inspection of exposure N-1 results.
1		
	Initiate IPS slew.	
2	Monitor maneuver and slew.	
	Reposition IPS star trackers.	
	Reposition focal plane sensors.	
3	Reposition diagonal mirror.	
4	Terminate IPS slew.	Command data storage.
	Terminate Shuttle maneuver.	
	Final settle.	Verify and correct instrument status.
5		
	Complete settle.	
	IPS star trackers signal lock-on.	
6	Focal plane sensors signal lock-on.	
	Field verification	Field verification.
7		
		Initiate exposure N.
8	Monitor SUOT and IPS performance.	Monitor instrument performance.
	Monitor and operate other payload instruments.	Review and correct command seque and parameters for exposure N+
	Monitor and correct attitude rates (once per 5 minutes).	
	Review and correct command sequence for exposure N+1.	Analysis and comparison of exposure N-1 results with previo data.
	Transmit exposure N-1 results when TDRS available.	
≈		≈
47		TERMINATE EXPOSURE N.

While the Mission Specialist has been setting up the telescope pointing and guidance, the Payload Specialist has been preparing instruments for data acquisition. During the slew (and after if necessary) the status of all instrument parameters has been called up from the computer, reviewed and corrected if necessary. These parameters include:

DIC: filter wheel position
intensifier voltage
sensor temperature
focus setting (dependent upon filter thickness)
film frame number
shutter (open or closed)

PCS: entrance slit width and decker position
filter wheel position
grating carousel position
detector carousel position
detector voltage

The SUOT Field Viewing Monitor may be used to examine the focal plane image and confirm that the star is precisely centered on the PCS slit. Fine pointing adjustments or precise offsets accurate to about $\pm$ 0.1 arc sec are required for the proper use of the PCS. Once all pointing corrections are complete, the DIC and PCS exposures are initiated.

During the data acquisition, status of both instruments is monitored. The output of the PCS is assumed to be accumulated in computer memory and the recorded spectrum is visually observed to build up by CRT monitor display. It is expected that during the relatively long SUOT exposures, the Mission Specialist (and possibly the Payload Specialist also) will have a significant amount of free time to monitor and control other instruments in the payload complement. Also, they should have time to review the pointings and command sequences for the next exposure and to revise them as necessary.

The exposure can be automatically terminated by computer or manually ended by the Payload Specialist. The data are read out onto temporary storage, and held for transmission to POCR as soon as TDRS is available.

During exposures the observing team both on board and on the ground are free to evaluate the data already recorded, which is in temporary storage both in the orbiter and at the POCR. If the data warrants, either because of unexpected scientific results or because of impaired data quality, additional observations of the objects in question could be programmed in real time.

SPECIAL NOTE:

Some concern is expressed about how the IPS will accomplish pointing to a few arc sec accuracy, and how much setup time will be needed. Field identification and pointing would be greatly facilitated by adding a 100 mm aperture, f/2 finder telescope with a 1 cm square charged couple device (CCD) array as a detector. This telescope would detect any star listed in the SAO catalogue; at least ten SAO stars should appear in the 3° field of view, even at the galactic poles.

With such a telescope, a useful technique to speed field identification and pointing would be to overlay the video display of the actual star field with a correctly oriented computer-generated star field derived from the SAO catalogue. Less than a minute should be necessary to identify the star field and correct the telescope pointing, either manually or by computer.